Saskatchewan
Agriculture
and Food

ADF

AGRICULTURE DEVELOPMENT FUND

FINAL REPORT

20010292 & 20040608

HYDROLOGY OF PRAIRIE CATTLE FEEDING OPERATIONS

Funded by: The Agriculture Development Fund
&
The Beef Development Fund

June 2007

Prepared by: University of Saskatchewan

Feedlot Hydrology
Final Report June 2007

ADF Project 20040608

Charles Maulé, P.Ag., Ph.D. Terry Fonstad, P.Eng, Ph.D.
Department of Agricultural & Bioresource Engineering
57 Campus Drive
University of Saskatchewan
Saskatoon , Saskatchewan
S7N 5A9

Acknowledgements

Funding: Saskatchewan Agriculture Development Fund. Horned Cattle Trust Fund, Saskatchewan Beef Development Fund.

Technical Support: The following personnel are thanked for their technical support: Iain Herzog, Marc White, Michelle Sander, Jon Henderson, Tanya de Rosario, Sumith Priyashantha, Daryl Rinas, and Kimberley Tang.

Lisa White is acknowledged for her significant contribution towards technical work and feedlot concepts with regards to Eston Feedlot.

In Kind and Access: PFRA is acknowledged for drilling and installation of piezometers, drill log interpretation and geotechnical laboratory analysis of core samples. Personnel at the River Ridge, Royal View, and University of Saskatchewan Feedlots are thanked for access permission and project support.

Abstract

The study objective was to develop a feedlot regional runoff model that can help runoff pond sizing. Results from three feedlots, laboratory work, and long-term climate records were used. The 24 hr 1-in-25 year rain amount within the agricultural region of Saskatchewan ranges from 62 to 78 mm, whereas the expected runoff, from such an event, is 29 to 46 mm, with the SE region being the wettest and the CW (central west) the driest. Seasonal (April 1 to October 31) 1-in-25 year rains (400 to 523 mm) and runoff amounts (62 to 112 mm) are recommended to use for runoff pond sizing.

Table of Contents

Executive Summary **1**
1. Introduction **4**
2. Literature Review **6**
2.1 Manure Pack Properties 6
2.2 Manure-Soil Interface Layer 6
2.3 Runoff 7
3. Materials and Methods **11**
3.1 Study Site Descriptions 11
3.2 Field Measurements 12
3.3 Laboratory Studies 17
3.4 Theoretical Development 21
4. Manure Pack and Feedlot Floor Results **27**
4.1 General Feedlot Pen Floor Conditions 27
4.2 Laboratory Determined Manure Pack Properties 31
5. Field Measurements and Model Development **37**
5.1 Cattle Input 37
5.2 Manure Pack Moisture; Measured and Modeled 37
5.3 Runoff Measurements 39
5.4 Modeling Runoff 41
6. Saskatchewan Climate and Feedlot Runoff **46**
6.1 Saskatchewan Climate 46
6.2 Feedlot Runoff 47
6.3 Feedlot Storage Pond 49
7. Summary, Conclusions, and Recommendations **51**
7.1 Summary and Conclusions 51
7.2 Recommendations 54
References **55**

Research Appendices: Volume II
Appendix A. Papers and Presentations
Appendix B. Extended Bibliography
Appendix C. Photographs and Maps
Project Appendices: Volume III

Commonly used symbols and abbreviations

Symbol	Units and Definition	Page number
AE	Actual Evaporation rate, mm/d	2
CE	Central east	3
CN	Runoff Curve Number	1, 8, 22
CNp, CNm	Predicted and observed CN values	42
CW	Central west	2
D	Storage pond seepage, mm	44
db	Mass moisture content on a dry basis, kg/kg	6
H	Storage pond depth of runoff, m	44
Ks	Saturated hydraulic conductivity	7
MSI	Manure Soil Interface	7
NE	North east	3
P	Precipitation amount, mm	9
Pc	Cattle contributed water, mm/d	37
PE	Potential Evaporation rate, mm/d	2
Pr	Rainfall, mm/d	37
R or RO	Runoff amount, mm	9, 22
S	Storage retention factor, mm	22
SE	South east	2
SM	Amount of moisture stored in manure pack, mm	37
SMp, SMm	Predicted and measured manure pack moisture, mm	38
SW	South west	2
SW	Water content of soil or manure pack, mm	23
VMC	Volumetric moisture content, m3/m3	2
VMCp	Predicted volumetric moisture content, m^3/m^3	42
wb	Mass moisture content on a wet basis, kg/kg	1

Executive Summary

Introduction

The goal of this study was to construct and validate a beef feedlot runoff model incorporating regional climate and soils conditions that will aid the sizing of runoff storage systems. Thus the primary objective was to develop a regional runoff model so that feedlot runoff within the agricultural region of Saskatchewan can be represented. To accomplish this main goal three secondary objectives had to also be investigated:

i. To determine the amount of moisture that can be stored and retained within the manure pack and surficial soil layer;
ii. To determine the amount of moisture that can drain (move downwards) from the manure pack and the surficial soil layer; and
iii. To determine the amount of moisture removed from the manure pack and surficial soil layer in response to evaporation.

Manure Pack Properties

The feedlot manure pack is critical to retaining water and preventing excessive runoff. A bare compacted feedlot surface has a very high runoff potential. A manure pack can detain moisture by absorption and surface detention. The moisture content of the feedlot manure pack can range from 0.02 to 0.70 kg/kg (wb) and rapidly absorbs water when dry. At moisture contents above 0.68 kg/kg the manure pack is a slurry if disturbed by cattle and will flow under its own weight. At these moisture contents the surface is smooth and will not detain any runoff waters and most of the rainfall will runoff. This report evaluates runoff with the use of a common and accepted method, that of runoff Curve Numbers. Runoff Curve Numbers (CN) are values indicating runoff potential and can be used to quantify the daily runoff amount (mm); the higher the value the greater the runoff from a given rain storm (SWAT, 2005; refer to Chapter 3 for a full description). At moisture contents of 0.52 to 0.68 kg/kg (wb) the manure pack is plastic, tending to retain shape if disturbed. Runoff still tends to be very high due to its wet conditions (CN 88 to 96). At these moisture contents the surface is very rough, as disturbed by cattle, and there is too much moisture for compaction. Moisture contents of 0.32 to 0.52 kg/kg (wb) the manure pack is moist and friable, clods can easily break up and the pack can become compacted by cattle. Runoff potential is low (CN 72 to 87). At moisture contents less than 0.32 kg/kg the manure pack starts to become dry to touch and brittle. Runoff potential is very low (55 to 71). Action by cattle results in a granular layer of manure on top of a compacted brittle impervious layer.

Undisturbed manure packs (bulk density of 477 kg/m^3) holds 0.59 kg/kg (wb or 0.69 m^3/m^3 volumetric moisture) at saturation and drains to 0.51 kg/kg (0.61 m^3/m^3) after 3 hours. The manure pack dry bulk density is within the range of 400 to 480 kg/m^3 unless appreciable soil is mixed within it (bulk density increases to 500 kg/m^3 and more), is composed largely of straw (bulk density decreases to 200 kg/m^3 or less) or is liquid (slurries can be 370 kg/m^3 in dry bulk density). Moisture draining through the manure pack and into the soil surface can remove excess water from the manure pack and from runoff. Manure packs with little soil and not compacted can have saturated hydraulic conductivities of 100 mm/hr and greater. Within an active feedlot pen excess rain water would rapidly drain to the bottom of a manure pack, however would soon become mixed

in by cattle, thus creating slurry conditions. Undisturbed soil cores of compacted manure and the manure soil interface had geometric saturated hydraulic conductivities of 3 to 5 x 10^{-6} cm/s (0.1 to 0.2 mm/hr). Due to these low rates we thus assumed that downward drainage was 0 mm/d and would have no impact upon water loss during a runoff event or upon decreasing the moisture content in a manure pack during very wet conditions that might prevail during a one week period.

A lab study of water evaporation from manure provided the following relationship of evaporation and manure pack moisture content:

$$AE = PE\ (1.42\ VMC - 0.02)$$

where AE is actual evaporation rate (mm/d), PE is potential evaporation rate (mm/d as determined from climate parameters), and VMC is volumetric moisture content of the manure pack. This equation is effective for VMC values between 0.02 and 0.69 m^3/m^3 for active feedlots in which the manure pack is disturbed (mixed). At values of 0.69 m^3/m^3 and above AE=PE.

When this equation is incorporated with climatic measurements of daily rainfall and PE, with a manure pack depth of 50 mm, and allowing for contribution of moisture by cattle (0.75 mm/d for this study) it provided a general representation of measured manure pack moisture contents. This manure pack water balance was used within the runoff model.

Feedlot runoff

A feedlot runoff model was developed using the manure pack water balance model from the previous section and the Curve Number Method (CN). This model was developed using field data measured from a Lethbridge feedlot (Miller et al., 2003, 2004b). With the exception of one out of 11 runoff events, our predicted CN model provided a good fit against their measured CN values. It was not possible to validate our model against other measured data sets as we did not succeed in obtaining working runoff weirs, however predicted runoff amounts, in general agreed, with observed (but not measured) runoff events.

Twenty-seven climate stations, with daily data from April 1 to October 31 for the years 1940 to 2006, were used to input rainfall and potential evaporation data into the runoff model. The 66 years of climate and runoff output data were used to develop maps showing 1-in-25 year 24 hr and seasonal maximum rainfall and runoff amounts. A model component calculated storage pond depth allowing runoff, rainfall, seepage, and evaporation into and from the pond. Only in one region of the province, the southeast (SE) did the 24 hour maximum rainfall with a 25 year return period exceed 75 mm. The driest portions of the province (SW and CW-Central West) had 24 hour maximum 1-in-25 year rainfalls of 62 mm. Maximum 24 hour 1-in-25 year runoff amounts ranged from 29 mm (central-west, CW) to 46 mm (SE). Of importance towards feedlot storage pond design should be that of seasonal runoff amounts; maximum 1-in-25 year runoff amounts ranged from 62 mm in the CW to 112 mm in the SE and 1-in-25 year maximum pond depths ranged from 2.3 to 3.5 m for the same regions. Current Saskatchewan regulations ask that feedlot storage ponds be able to accommodate 75 mm of runoff from a daily rainfall. Such an amount would only occur for frequencies much in excess of a 1-in-100

year rain event. A 24 hour 1-in-25 year rain event for the agricultural region of the province is 68 mm, whereas a 24 hour 1-in-25 year runoff event averages 37 mm (Table 1). It would be more appropriate to design storage ponds upon expected accumulation of seasonal runoff and rainfall minus seepage and evaporation losses in the runoff storage pond. Seasonal 1-in-25 year maximum rainfall amounts is 470 mm. Seasonal 1-in-25 year maximum runoff is 90 mm, and seasonal maximum storage pond depth is 3.0 m. These seasonal amounts will range by 50% between the dry (SW and CW) and wet regions (SE, CE, and NE) of the province and thus regional differences should be accommodated.

Table 1. Climatic and feedlot runoff summary for Saskatchewan Agricultural Regions

Region	Crop District	average seasonal rain mm	1-in-25 yr max. seasonal rain mm	1-in-25 yr max. 24 hour rain mm	1-in-25 yr max. seasonal runoff mm	1-in-25 yr max. 24 hr runoff mm	1-in-25 yr max. storage depth m
SE	1,2, 3ASE, 5A	334	523	78	112	46	3.48
SW	3 ASW, 3AN, 3BN, 3BS, 4	267	418	62	72	33	2.51
CE	5, 6A	312	497	69	100	39	3.22
CW	6B, 7	269	400	62	62	29	2.28
NE	8, 9AE	323	487	66	97	39	3.21
NW	9AW, 9B	309	458	63	85	34	2.90

Regions and Crop District refer to agricultural portions within the province by Saskatchewan Agriculture and Food (http://www.agr.gov.sk.ca/). Refer to Fig. 3.10. **'Seasonal'** includes all rain or runoff from April 1 to Oct 31. **Storage depth** is depth of accumulated runoff in storage pond such that 75 mm of runoff would be 2.7 m deep, 90 mm 3 m, 100 mm 3.2 m deep.

Recommendations

The following recommendations are for aid in sizing of feedlot storage ponds within the agricultural region of the province:

1. Storage ponds that are to be emptied only once, at the end of the rain season, should be designed upon seasonal (April 1 to October 31) 1-in-25 year maximum runoff. For dry regions of the province this will be 62 mm, however for wet regions of the province this will be 112 mm. These amounts do not include snowmelt runoff.
2. Sizing ponds based upon a daily runoff event of 75 mm is far too great for any 24 hr, 1-in-25 year runoff event and is even greater for than any 24 hr, 1-in-100 year runoff event, however is appropriate for some seasonal 1-in-25 year runoff amounts.
3. Within the dry regions of the province (SW and CW), storage ponds designed to hold 3 m depth, resulting from 75 mm of runoff will be dry at least 25% of the time. These regions could have storage ponds designed for evaporative control rather than emptying for irrigation.
4. Sizing ponds based upon maximum expected daily runoff does not allow for seasonal accumulation unless they are to be emptied several times a year.

1. Introduction

Statement and Relevance. Containment of feedlot runoff is important to prevent pollution of lands and water ways. Design of adequate containment systems involves knowledge of feedlot hydrology and regional climate. Feedlot hydrological parameters include infiltration and retention of water into feedlot manure pack and feedlot floor, drying rate of manure pack between runoff events, and the contribution of cattle to feedlot runoff. Climate parameters include rainfall amounts, rates, and frequency of occurrences, and intensity and frequency of drying periods between rainfall events.

Purpose. The overall purpose of this study is to define the hydrology of prairie cattle feedlot pens with emphasis placed upon determination of predicting the frequency and intensity of runoff events. The goal is to construct and validate a runoff model that incorporates regional climate and soils conditions that will aid feedlot design. Such a model can also be used for of transport of nutrients and pollutants. .

Objectives: Within the context of determination of the hydrology of feedlot pens with emphasis placed upon runoff (Figure 1.1) the primary objective of this study is:

1. To develop a simple regional runoff model such that the probable frequency and intensity of runoff can be determined given the following parameters:
   - Daily rainfall amount;
   - Atmospheric drying conditions (potential evaporation);
   - Manure pack properties (thickness, moisture content, roughness, composition); and
   - Soil properties (moisture content, texture, bulk density, hydraulic conductivity).

Measurement and determination of the parameters associated with objective 1 will enable the following secondary objectives:

i. To determine the amount of moisture that can be stored and retained within the manure pack and surficial soil layer;
ii. To determine the amount of moisture that can drain (move downwards) from the manure pack and the surficial soil layer; and
iii. To determine the amount of moisture removed from the manure pack and surficial soil layer in response to evaporation.

This report does not cover snowmelt runoff, seepage rates and depth of seepage into feedlot mineral floor or storage ponds, and runoff chemistry.

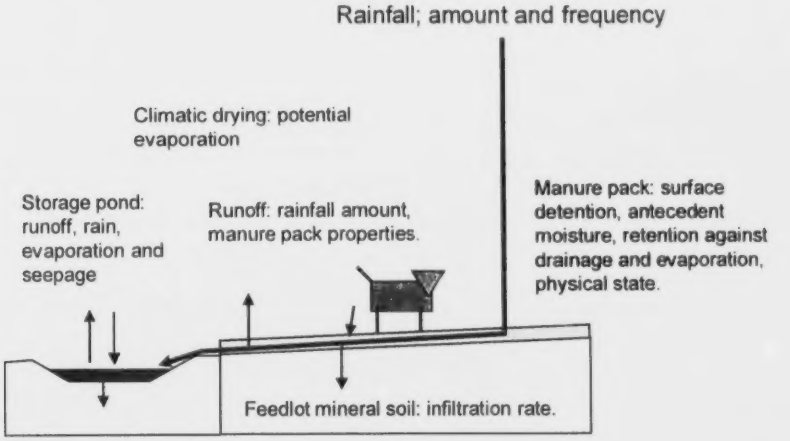

Rainfall; amount and frequency
Climatic drying: potential evaporation
Storage pond: runoff, rain, evaporation and seepage
Runoff: rainfall amount, manure pack properties.
Manure pack: surface detention, antecedent moisture, retention against drainage and evaporation, physical state.
Feedlot mineral soil: infiltration rate.

Fig. 1.1. Conceptual representation of feedlot hydrology with emphasis placed upon runoff.

Deliverables: The objectives will be realized with the following products pertinent to the agricultural region of Saskatchewan:

1. Produce maps showing rainfall expected for 24 hour, 1-in-25 year rain storms. This criterion is used by others (e.g. United States – see Safley et al., 1996) to aid with runoff design of feedlots.
2. Assess the occurrence of a 75 mm 24 hr rain and runoff events. A runoff event of 75 mm is used for feedlot pond design purposes in Saskatchewan (SAF, 1999).
3. To produce maps showing extreme (1-in-25 year) seasonal rainfall and runoff amounts (April 1 to Oct 31st).
4. To develop a manure pack characterization chart that indicates it's potential to absorb rain and/or to result in runoff.
5. To develop and test a feedlot runoff model that adequately predicts daily runoff given rainfall, potential evaporation, and manure pack conditions.
6. To produce a seasonal 1-in-25 year maximum storage pond depth, allowing for pond seepage, rainfall, and evaporation.
7. To provide recommendations for runoff storage pond sizing so as to adequately account for 1-in-25 daily and seasonal runoff events.
8. To provide the above information for 1-in-50 year events.

2. Literature Review

2.1 Manure pack properties

The composition of the manure pack is primarily organic and will vary with decomposition and feed type. The physical properties of the manure pack; e.g., bulk density, moisture content, volatile solids, ability to absorb, conduct and retain water are going to vary with depth, age, climate, age of manure, frequency of pen cleaning and stocking density.

Cattle, in the weight range of 340 to 500 kg (feeders) will excrete about 58 kg d^{-1} 1000 kg^{-1} of live animal mass (Barth et al., 1996; ACFA and AAFRD, 2002) of feces and urine. Total solids (dry matter) in the excreted manure will be 14.6 %, on a wet basis (wb), (ACFA and AAFRD, 2002; ASAE, 2003) which assuming a manure density of 1000 kg m^{-3} (ASAE, 2003) for freshly excreted manure has a moisture content of 85.4 % (wb). Thus 1000 kg of live animal mass will excrete 49.3 kg of water which will be equivalent to 2.46 mm of water per day in given a stocking density of 20 m^2 per 1000 kg. Within the pen processes of decomposition (Powers and Van Horn, 2001, assumed 20% dry matter loss by anaerobic or aerobic fermentation), trampling, climatic drying and wetting, will alter the physical and organic matter make up of the manure pack. If the total solids content is less than 9% (wb) then the manure has the properties of a slurry, between that of 11-15% it can still have some fluid prosperities when subjected to a shear force but is more of a semi-solid and above 19% beef feeders' manure is classified as a solid (Laguë et al., 2005). At total solids greater than about 11 % (wb) or moisture contents less than 89% a manure pack can maintain a rough surface and thus have the ability to detain surface ponded water from running off. Moisture contents of feedlot manure, which is important upon removal, is estimated at 50% (wb) within Alberta (ACFA and AAFRD, 2002) on an annual basis, 45% (wb) as estimated within the US (Barth et al., 1996) for unsurfaced lots in dry climates (annual rainfall of less than 150 mm) with annual removal and has been reported as varying from about 54%, on a dry basis(db), for feedlot removal in July to 119% (db) for manure removal in December (Gilbertson et al., 1971).

In order to maintain animal health and reduce tag, bedding materials are commonly added to a central mound in the feedlot. Bedding material is 1 to 2 kg per animal per day (ACFA and AAFRD, 2002) and 2.5 kg straw per 100 kg of animal weight is recommended by SAF (2004) daily to 3 times a week. This alters the physical properties (density, water retention, surface roughness) of the manure (Olson et al., 2003).

Manure bulk densities have been reported as being in the range of 290 to 960 kg m^{-3} (Miller et al., 2003), although Mielke et al (1974) report that typical bulk densities are in the range of 750 to 930 kg m^{-3}.

2.2 Manure-Soil Interface Layer

This layer is of mixed organic matter and mineral soil on top of the soil. Its formation is due to a complex interaction of compaction and grinding from cattle hooves, manure accumulation, biochemical reactions and anaerobic conditions. An excellent description

of this process is given by Mielke et al. (1974) and supported or developed further by Kennedy et al. (1999) and Miller et al. (2003). The conditions in an active feedlot with a manure pack results in a black ashy (Kennedy et al., 1999) layer that is relatively impermeable to water and air (Mielke and Mazurak 1976). Several studies have determined Ks from undisturbed cores; Miller (1971) reports values of 0.1 x 10^{-6} cm/s to 10 x 10^{-6} cm/s; Mielke and Mazurak (1976) from 6.3 to 131 x 10^{-6} cm/s; McCullough et al (2001) from 0.5 to 1.9 x 10^{-6} cm s^{-1}. Field measurements tend to be more variable depending upon the method; ponded water infiltrometers recorded values of lower than 4 x 10^{-7} cm/s (Kennedy et al., 1999), use of a disc permeater obtained values of 2 x 10^{-6} cm s^{-1} (Southcott and Lott 1997), and use of a tension infiltrometer found values of 4 to 9 x 10^{-4} cm/s (Miller et al, 2004a,b). These values are generally one to two orders of magnitude lower than the surface, as packed by machinery but before cattle were ever stocked (Kennedy et al., 1999; Southcott and Lott 1997; and McCullough et al 2001) or than that of the soil immediately underlying the manure-soil-interface (MSI) (Miller et al 2003). With the use of solutes present in manure (Cl^- and NO_3^-) Maule and Fonstad (2002) determined that long term (25 to 30 years) moisture seepage fluxes through the feedlot surface was between 2 and 5 mm/year in central Saskatchewan.

2.3 Runoff

Rainfall runoff

Previous studies have related the occurrence of feedlot runoff to individual rain events in several ways (Table 2.1):

1. Regression equations giving the amount of runoff expected for a rainfall event;
2. Minimum amount before runoff begins;
3. The proportion of runoff to event or total annual rainfall; and
4. Curve numbers for use with the USDA runoff model (Soil Conservation Service 1972).

A number of studies, especially early ones, developed runoff equations by regressing runoff amount against the daily or seasonal rainfall amount for the location (Table 2.1). Some of these feedlot studies obtained strong correlations (Swanson et al. 1971; Manges et al., 1971, Gilbertson et al., 1971; Clark et al., 1975, Kizal 2003), however Miller et al. (2004a,b) could not obtain any relationship with their 11 events as collected over 5 years. Clark et al (1975) found that a steeper slope and higher intercept (minimum rain needed before runoff began) occurred with Texas feedlots than that of Nebraska or Kansas. They attributed this to drier manure pack conditions and their ability to absorb more water. Several researchers (Swanson et al. 1971; Gilbertson et al 1971; Clark et al. 1975) report that about 10 to 13 mm of rain is needed before runoff is to begin unless there had been rainfall within the previous 72 hours (Swanson et al., 1971). Miner et al (1966), from simulated rainfalls of 70 mm in one hour, found that about 20 mm of the rain was stored in a 'moderately dry to moist' manure pack and did not runoff.

The proportion of runoff from individual rain events was found to vary from 0.1% to 56% (Miller et al., 2004a). Madden and Dombush (1971), in South Dakota reported that 20% of the annual total runoff occurred from the single largest rain event, whereas 50% of the runoff would be from numerous small events, which would not likely cause runoff

in adjacent agricultural lands. Kennedy et al (1999) noted that there were two types of rain events producing runoff; short intense rains producing only small amounts of runoff, and long duration rains which produce more runoff, but also resulted in the manure pack storing more water.

Curve Number (CN) values are extensively used to plan feedlot storage ponds within the United States (Phillips 1981; USDA 1996). CN values provide an quantitative assessment of runoff amount given a 24 hour rain event and the selection of the CN value is based upon soil type and land use can be assessed for most types of land. A technical explanation and guideline for use can be found in the NRCS Hydrology Manual, Part 630 (NRCS, 2001). High CN values 85 to 97 generally occur for very wet to compacted soils or that of pavement. Forested soils in good condition and of sandy texture may have CN values as low as 30, row crops may be 75, and bare soils 85. Dry conditions and or sandy textured soils will have lower CN values then wet or clay soils. Once the CN value of a soil and land use is found, then simple equations can estimate runoff given a 24 hour rain storm. CN values, for feedlots, for individual runoff events, have been reported as ranging from 52 to 96 (Kennedy et al., 1999; Miller et al., 2004a). This range of values for individual rain event for both runoff percent and for CN value is attributed to rainfall amount and intensity and the storage ability of the manure pack. Caution must be given to application of these values to any single rain event as these values were only generated from rain events that resulted in runoff. A CN value of 90, for earthen floor pens, is recommended for designing runoff feedlot ponds in the United States for a one in 25 year, 24 hr rain event (Phillips 1981; USDA 1996). USDA (1996) recommends a CN value of 90 for unpaved feedlots and 97 for paved adding that "based on these CN's, the amount of runoff from feedlots can be estimated as a percentage of the precipitation that is expected over a period of time."

High CN values have been recorded by a number of researchers. Bergsrud (1968) and Fields (1971) recorded values of 90 and 91 at Kansas feedlots, however Wensink and Miner (1975) state that runoff events in Kansas and Minnesota are from mainly catastrophic rainfall conditions. Larson et al. (1976) state that maximum runoff rates from feedlots or other small areas are generated by high intensity storms of short duration. Kizil (2003) found that a CN value of 93 provided best fit to a number of runoff events from a bison feedlot in North Dakota. The heavy weight of the bison and that the feedlot floor was soil mixed with fly ash might have made for greater runoff. Miller et al (2004b) recorded four rain events of between 90 and 96 which were not always from intense rain storms or/and having wet antecedent conditions. Although some of these high values measured by others or recommended by some (Phillips 1981) they appear to be for extreme events or/and within wetter climates.

Varying the CN value as dependent upon antecedent conditions has been attempted by on a few researchers. Wensink and Miner (1975) and Larson et al (1976) used a 5-day antecedent precipitation amount of 53.3 mm (for when preceeding 5-day average temperature >4.4°C) to choose a CN value of 91 (dry conditions) or 97 (wet conditions) for runoff modeling under wet conditions of Oregon or Minnesota. Overcash and Phillips (1978) report on antecedent moisture corrections by Woolhiser (1975) from Colorado

conditions: if 5-day antecedent rainfall is <36 mm, a CN of 78 is assigned; 36 – 53 mm, CN of 90; and >53 mm then a CN of 96 is used. Miller et al., (2004a) determined 5-day antecedent values for individual events but obtained no relationship with measured CN values. Despite numerous recommendations to use CN values of 90 or greater for rainfall events upon earthen feedlots, several studies report CN values from individual events to range: Overcash and Phillips (1978) determined the CN value for numerous other studies in Nebraska and Texas (Swanson et al 1971; Gilbertson et al 1972; Clark et al 1975) and found CN values to range from 65 to 95; Kennedy et al (1999) in central Alberta obtained CN values between 55 and 83; and Miller et al (2004a) in southern Alberta obtained CN values between 52 and 96.

Table 2.1. Runoff findings reported by other studies

Runoff equation	Pmin	units	Comment	Author
R = 0.93P-10.3	11	mm	Eastern Nebraska, 1968 runoff	Swanson et al 1971
R = 0.445 P - 1.3	3	mm	Eastern Nebraska, 1969 runoff	Swanson et al 1971
R = 0.493 P - 1.5	3	mm	Eastern Nebraska, 1970 runoff	Swanson et al 1971
R = 0.57 P -3.6	6	mm	Kansas; 2 acre feedlot	Manges et al., 1971
R = 0.593 P - 3.3	6	mm	Kansas; 33 acre feedlot	Manges et al., 1971
R = 0.531 P - 3.4	7	mm	Nebraska, 1968-69	Gilbertson et al., 1971
R = 0.885 P - 11.9	14	mm	Texas, estimated from graph	Clark et al., 1975
R = 0.57 P - 1.2	3	mm	N. Dakota, flyash soil feedlot for Bison	Kizal, 2003
R = 0.318 P - 2.8	10	mm	N. Dakota	Swenson, 1975
na	13	mm	min rain unless rain in last 72 hrs	Swanson et al. 1971
na	11	mm	min rain for runoff to occur	Gilbertson et al., 1971
na	10	mm	min rain for runoff to occur, Texas	Clark et al., 1975

Runoff	units	Comment	Author
20	%	of annual runoff; single largest event	Madden and Dornbush 1971
70 (44)	%	of winter ppt (Dec thru Mar), Nebraska mostly snowmelt (% of annual runoff)	Gilbertson et al 1971
50	%	% of total annual runoff, from 10 rain events that usually do not produce runoff in agricultural lands	Madden and Dornbush 1971
39/29	%	Of annual ppt, Nebraska	Nienaber et al., 1974
19-25	%	Of annual rainfall in eastern Canada	Coote and Hore 1977
16 to 40	%	of individual rainfall events	Kennedy et al., 1999
0.1 to 56	%	runoff yield of individual rain events	Miller et al., 2004a

CN value	Comment	Author
82	13 m^2/hd, paved and unpaved same	Hauser 1975
82	85 m^2/hd, low density, diary feedlot	Swenson,1975 in Kizal, 2003
90-97	Dry conditions 91, wet conditions 97. Minnesota, Kansas. Events in these states are mainly catastrophic (Wensink and Miner 1975)	Bergsrud, 1968 Fields, 1971 Wensink & Miner, 1975 Vanderholm et al., 1979
91		Miner et al., 1979
90	Recommended for earth lots in US	Phillips 1981, USDA 1996
55-83	central Alberta, rain amounts need checking	Kennedy et al., 1999
93	bison feedlot, 93 gave best fit to events	Kizal, 2003
52-96	for 11 events over 5 years, Lethbridge	Miller et al,. 2004a

It could be that values of 90 and higher occur in more humid climates where evaporation cannot sufficiently dry out the feedlot and in climates where annual potential evaporation is greater than precipitation the manure pack can dry out and CN values of lower than 90 can occur.

Snowmelt runoff

Limited studies have been done upon snowmelt runoff from feedlots. Within the prairies about 30% of the annual precipitation occurs as snow between November 1 and March 31, which generally does not melt until the end of March, with the exception of the Chinook region of southern and western Alberta and the occasional mid-winter melt. Snowmelt in the prairies can contribute more than 85% of the total annual runoff (Nicholaichuk, 1967; Card, 1979). On agricultural fields the soil is frozen during spring snowmelt and the ice blockage of pores reduces infiltration considerably (Gray et al., 1985), thus creating a high proportion of runoff relative to water in the snowpack. Within feedlots it is conceivable that the snow will be mixed into the manure pack to some degree and the lack of evaporation during the winter will mean that the feedlot pen could be very wet with the accumulated snow and water excreted by the cattle. One study that did measure snowmelt runoff in South Dakota (Madden and Dornbush 1971) found that of 10 feedlots (4 in 1969 and 6 in 1970) snowmelt accounted for between 2.8% and 82% of annual runoff (39 to 300 mm), for an average of 23% (46 mm) of total annual runoff (197 mm). The authors did not state snowpack accumulation values. Gilbertson et al (1971), reports upon snowmelt runoff from a Nebraska feedlot stocked at high density (9.3 m^2/hd) at being 68 mm for 84 mm (snow water equivalent) of snowpack accumulation and for low density feedlots (18.6 m2/hd) runoff was 45 mm. Snowpack amounts within feedlots will be difficult to predict. Snowpack development is affected by wind and cattle fences and feedlot windbreaks are often designed to minimize snowpack development within yards. Kennedy et al (1999) in their study in central Alberta reported that the feedlot operators removed the manure and snowpack before melt, thus there was no snowmelt runoff to report. We noted that in the feedlots in Central Saskatchewan, that just following melt in the fields that the manure around the central straw mound would be cleaned out before it could fully thaw. Miller et al (2004a) in a five year monitoring study of feedlot runoff in Lethbridge found that all runoff events were caused by rainfall. Chinnooks of that region could have been responsible for minimizing the snowpack and perhaps midwinter drying of the manure pack. Given that snowpack runoff from an agricultural field is generally 30-50% of the snowpack SWE and is related to antecedent moisture content, it can be expected that snowpack runoff from a not cleaned feedlot could be more, given cattle additions, and being mixed in with straw and manure.

3. Materials and Methods

The study had three components; field, laboratory, and modeling. Measurements from the field and lab studies enabled development of a runoff model and application to the agricultural region of Saskatchewan.

3.1 Study Site Descriptions

The field portion of the study took place at three feedlots; one near Eston (fall 2002-spring 2005) and two near Saskatoon (spring through fall 2005 and spring through summer 2006).

Eston Feedlot

This feedlot was first established in 1996 of 8 pens each 75 by 75 m. In 2001 another 8 pens of similar dimensions were built and stocked by the end of the summer of 2001. The pens were arranged along a road, 8 on each side with a 1.5 % slope away from the center road towards storage ponds bordering the outside. Stocking rates were about 100 head per pen of backgrounding cattle weighing about 360 kg. Bedding consisted of straw and pens were cleaned in the fall of each year. Our study was in pen 4 (1996 construction) and pen 6 (2001 construction). Cattle were present in the pen 4 until August 2003 and pen 6 until July 2003 with no cattle after those dates due to closure of the feedlot. Our study was from fall 2002 to spring 2005.

The feedlot is located in one of the drier parts of the province. Long-term precipitation, as recorded at Eston is 297 mm of which 63 mm occurs during the winter (Nov thru March) and 183 mm during the four summer months of May thru August (Canadian Climate Normals 1971-2000 at Environment Canada, 2007a). Long term average annual temperature is 3.0°C with January being the coldest month (-14.5 °) and July being the warmest (18.1°C).

The land about the feedlot, is of glaciolacustrine material with hummocky surficial features. The groundwater table is estimated to be between 5 to 8 m in depth as this was the depth that seepage conditions were encountered in drilling. Elevation in the SW ¼ of section 28 is 648 m (2125 ft) and varies by 1 to 2 m across the site.

Saskatoon Locale 1

The pens of this site were established in 1965. The pens are research focused and thus are small, 11 by 24 meters and commonly had between 3 and 10 cattle ranging from 200 to 500 kg in mass. Slope was about 1.5% towards the access road where the feed bunks were, however the concrete base of the feed bunk often prevented runoff from exiting the pens into the road drainage system. During our research period cattle were present in one pen (pen 1) year round and in the other pen (pen 2) during fall through spring, but not during the summers. Bedding was straw and the pens were cleaned in spring and fall.

The average annual temperature is 5.2°C, with January temperature at -16.4°C and July at 18.3°C. Long term annual precipitation is 348 mm of which 80 mm is winter (Nov through March) and 197 mm is summer (May through August) (Environment Canada, 2007b, SRC station).

The site was formed from alluvial material. The surface material in the pens were predominantly sand. The groundwater table beneath the pens was likely more than 5 m in depth and could be as much as 8 m.

Saskatoon Locale 2

This site was located near Saskatoon and was established in the late 1960's. This is a commercial lot consisting of about 40 pens of various sizes. Two pens were studied; were about 40 m x 40 m. The slope in pen 36 varied from 1 to 3% with a small depressional area in one corner where runoff accumulated and if deep enough flowed out into a pen road drainage ditch. The feed trough and concrete base was at the upper end. Straw bales were put in the middle (fall through to spring) and resulted in a mound, about 1-1.5 m higher than the surrounding by the end of the winter. Pen 42 also had the feed troughs and concrete base at the upper end. Runoff water tended to accumulate at the lower end and sometimes in the middle and if deep enough flowed into a fenced off pond or into a pen road drainage ditch. For both pens much of the runoff remained in the pens as scraping over the years had lowered the interior surface. The pens were scraped when needed. During our study we observed scraping during; June 2005, fall 2005, spring 2006 (except for the straw mound) and again in late summer 2006. Stocking rates varied between 60-70 head (150-200 kg) to 40 head (300-500 kg). Using the long-term climate data from the Saskatoon Airport, the average annual temperature is 2.2°C, with January being -17.0°C and July at 18.2°C. Annual precipitation is 350 mm with winter precipitation (Nov thru March) at 69 mm and summer (May thru August) at 209 mm. Surface soil ranged from sand to loamy sand. Water table was at about 2 m depth.

Field Measurements

Climate

Meteorological stations were set up at each of the three sites to record rain, temperature, humidity, wind and solar radiation. Data was recorded and stored in 10-15 minute intervals for rain and 30 minute intervals for the other parameters. Winter data was not collected at the Saskatoon sites and only partially available at the Eston site. Sensor, logger, or battery failures meant that data was approximately 60-70% complete for the summer seasons. Climatic data from Kindersley was used to supplement Eston feedlot data and climatic data from the Saskatoon Airport and the SRC Climate station was used for the Saskatoon feedlots. Climatic information was used to supplement observations and measurements upon runoff and water retention by feedlot manure packs.

Sampling

Manure pack and feedlot floor samples were taken at all three feedlots for determination of moisture content, bulk density, and hydraulic conductivity. Eston was sampled about 6 times for variation of moisture content with time, whereas the two Saskatoon feedlots were sampled about 30 times. About two thirds of the samples were undisturbed, using a 75 mm dia. by 50 mm high metal core for manure and soil and a 75 mm dia by 100 or 200 mm high metal cores for deep manure samples. Disturbed samples were by shovel or hand auger. Bulk densities were measured from undisturbed core samples. Saturated hydraulic conductivities, using falling head or constant head methods, were measured in the lab on core samples.

Runoff Weirs

A pen runoff collection and monitoring system was established for Two pens in the feedlot near Eston and for groups of pens at the two Saskatoon feedlots (Figs. 3.1, 3.2). Actual runoff was to be measured with a collection system comprised of several sections of PVC half pipe (0.6 m diameter) that funneled runoff water to a V-notch weir. At Eston each of the two pens had small earthen berms (100 mm height) installed at each corner of the lower slope end of the pen to direct all runoff toward the weir contained in a black plastic tub. These pens were not active at the time. The weir was covered with a piece of treated plywood to keep out debris and additional precipitation. The V-notch weir was 406 mm high, 337 mm wide, and was angled at 22.5°. The height of water in the stilling well was measured every five minutes by a pressure transducer placed inside a flexible bladder filled with antifreeze. The V-notch weir was used to calculate actual runoff flow from the pens based on the equations described in Gray (1970):

Fig. 3.1 and 3.2. Runoff collection system, weir, and data logger. PVC half pipe collected runoff from pen (behind fence) and channeled it through V-notch weir (in black plastic tub halfway down slope. Stilling wells (green and white cylinders) contained pressure sensor. Data was stored in module inside blue lidded plastic box.

Rainfall Simulator

A rainfall simulator was used to produce measured and constant rainfall rates so that runoff and infiltration could be measured and the CN value determined. A rainfall simulator was used twice: on the feedlot at Eston and on prepared manure surfaces at one of the feedlots near Saskatoon.

The following is text summarized and modified from White (2006). Infiltration and runoff rates for the feedlot near Eston were measured with a modified Guelph Rainfall Simulator (GRS II) based on a design by Tossell et al. (1987, 1990). The tests were done over a period of several weeks from September 4th to September 18th, 2003. The rainfall simulator consisted of a nozzle suspended over a 1 m^2 plot area. Consistent rainfall intensity was simulated with selection of an appropriate nozzle type, the height of the nozzle over the plot, and the water pressure at the nozzle. A 14W 1/4" nozzle was set 1.1 m above the ground surface at approximately 100 kPa pressure. A total of nine rainfall trials were conducted; three with a manure pack and six with the manure scraped off so to expose the surface of the mineral soil. Nolan et al. (1997) built a GRS II to study soil erosion in Alberta and noted that an intensity of 60 mm/hr typically represented Alberta storms and that running the simulator at this intensity for 20 minutes roughly mimics a one in two year storm. A rainfall intensity of between 34 to 68 mm/hr was simulated. A range of rainfall intensities was used because it was unknown as to what intensity of rainfall would produce runoff at the feedlot. When lower rainfall intensities did not generate runoff in a reasonable time frame (several hours or more), the intensity was increased. Runoff was contained to a 1 m^2 area by metal plates that were hammered into the ground to 15 mm depth (Figs. 3.3 and 3.4) and directed flow into a triangular runoff pan (Fig. 3.5). The runoff pan was sloped so that sediment flowed off the pan into a 500 ml mason jar. The time that rainfall started, that runoff began, and how long it took to fill the mason jars were noted. After a constant runoff rate was obtained (three successful similar times to fill a mason jar) the rainfall collector was shut off. The steady-state runoff rate was taken from the average of the last three runoff measurements. The infiltration rate was calculated by subtracting the runoff rate from the rainfall rate. Three uniformity tests were performed on the rainfall simulator by using nine rainfall collectors equally spaced under the nozzle using field operating conditions. The depth of water in each rainfall collector was measured after 20 minutes. The average uniformity of the measured rainfall intensity using Equations 3.1 and 3.2 (from Tossell et al., 1990) was determined to be 82.9%.

$$\text{Uniformity} = 100 \times (1 - \text{DEV}) \tag{3.1}$$

Where:

Uniformity = uniformity coefficient (%)

DEV = deviation of rainfall intensity

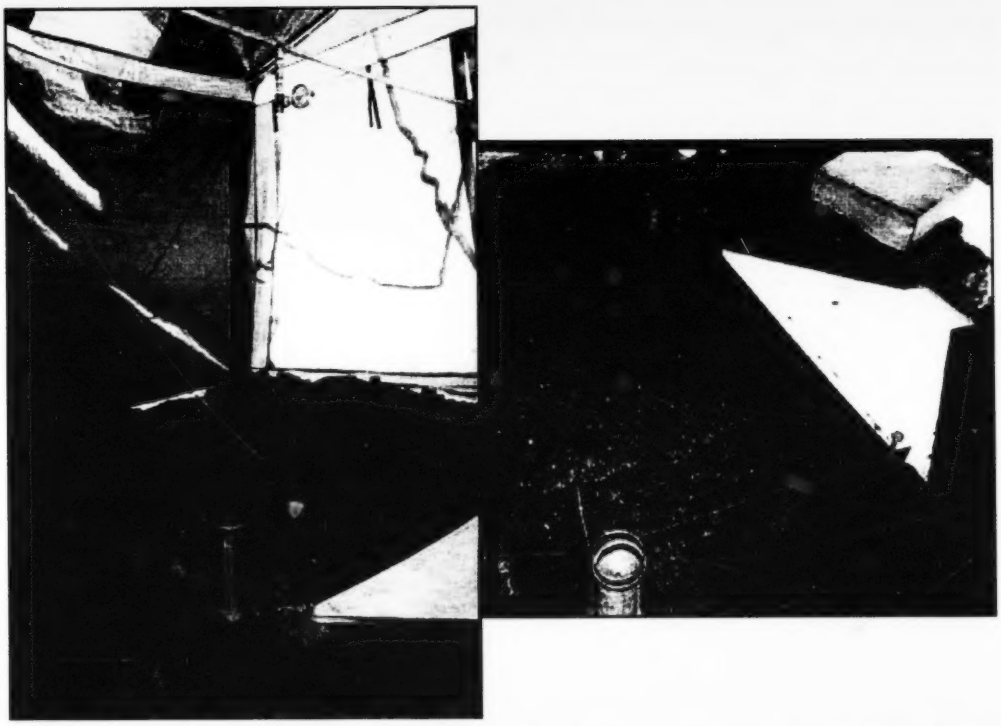
$$DEV = \left| \frac{(RI - meanRI)}{meanRI \bullet \#collectors} \right| \tag{3.2}$$

Where:

RI = rainfall intensity (mm/hr)

MeanRI = mean rainfall intensity for all rainfall collectors

collectors = total number of rainfall collectors



Figs 3.3 and 3.4. Rainfall Simulator. The simulator sprays water from a nozzle at a fixed height from the ground. A tent is around the setup to avoid spray being blow by the wind. Under the nozzle is a 1 m^2 area partitioned with metal sides so to focus runoff water into the metal collection plate. Under the narrow end of the collection plate jars collect runoff. The length of time it takes to fill a jar provides the runoff rate.

Rainfall Runoff Boxes

A rainfall simulator was also used on prepared manure surfaces at one of the Saskatoon feedlots. Four wooden boxes, approximately 0.60 m x 0.60 m area were prepared to different depths of manure at different moisture contents and then rained upon to determine the effect of manure depth and moisture content upon runoff (Figs. 3.5 and 3.6). The rainfall simulator consisted of one nozzle about 0.6 to 1.0 m above the manure surface. The length of time until ponding and until runoff were measured, as well as the runoff rate and rainfall rate. A shroud protected the application from wind.

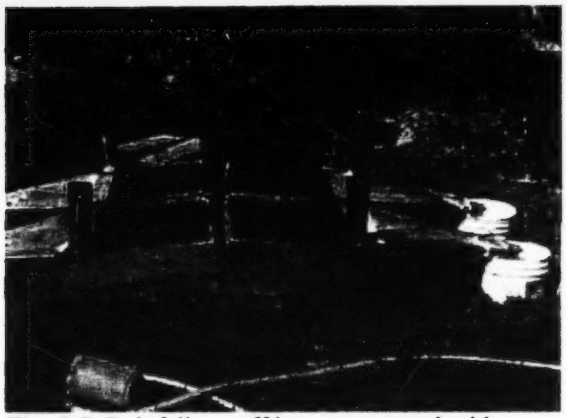


Fig. 3.5. Rainfall runoff boxes prepared with manure. At each corner and in center are rain gauges used to calculate rainfall rate. Runoff was collected in metal aprons and funneled to white buckets for measurement.

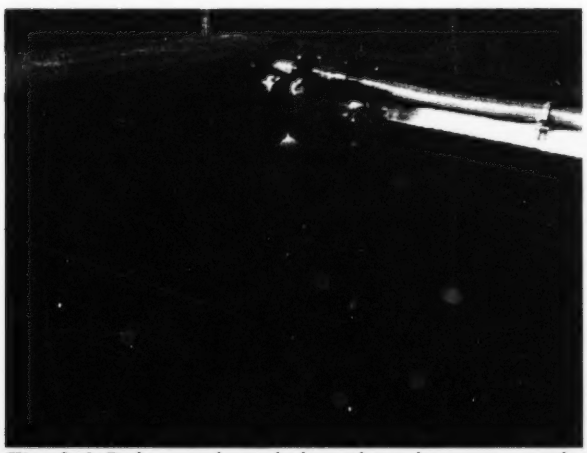


Fig. 3.6. Rain nozzle and shroud used to protect rain from wind.

Double Ring Infiltrometer

Summarized and modified from White (2006). Ponded infiltration was measured with a double ring infiltrometer (Fig. 3.7) in September of 2003. The purpose of this method was to give a measure of the steady-state infiltration (which under various assumptions can be similar to saturated hydraulic conductivity) of the feedlot floor.

The rings were hammered into the manure pack to an approximate depth of 30 mm. Due to the hardness of the compacted manure layer of the dry manure pack, as well as the soil underlying the manure pack, it was only possible to hammer the rings into the manure pack (not through the manure pack and into the soil). The diameter of the inner ring was 310 mm and the outer ring was 610 mm. A constant height of water of 150 mm was maintained in the inner ring throughout the experimental run. Water in the outer ring

reservoir was kept at the same height as the inner ring to prevent the lateral movement of water beneath the inner ring, thus maintaining vertical one-dimensional flow.

Height drop measurements were taken every minute until steady-state infiltration was reached, and every five minutes after steady-state had been reached. Steady-state infiltration was determined as having three similar drops in height of ponded water over the five minute measurement period. The cumulative infiltration measurements were then converted to an infiltration rate.

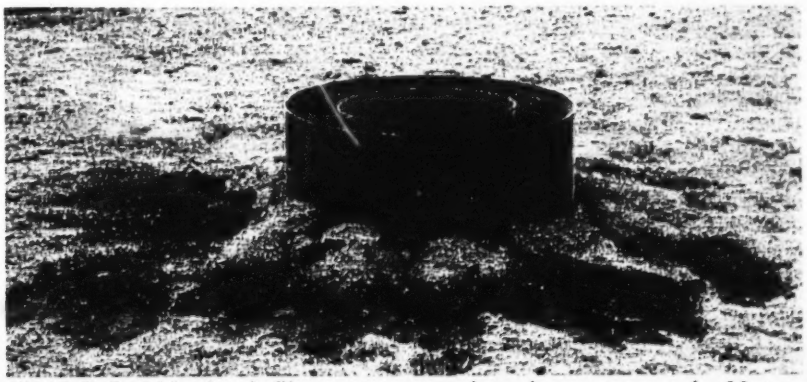


Fig. 3.7. Double ring infiltrometer set-up into dry manure pack. Note seepage from outer ring. Results from these tests were not used due to poor sealing with soil layer.

3.3 Laboratory Studies

To properly characterize feedlot properties important to the hydrology of runoff, the following measurements were done on feedlot manure pack and earthen floor samples under controlled laboratory conditions:

- Bulk density and saturated hydraulic conductivity of undisturbed cores;
- repacking and consequent bulk density and hydraulic conductivity;
- water retention at saturation and after gravitational drainage;
- water retention against evaporation
- manure physical state vs moisture content;

The setup of these tests are described further in the next sections.

Bulk density of soil samples at Eston Feedlot (modified from White, 2006)

Bulk density tests were conducted on 25 and 50 mm lengths of undisturbed soil samples from 200-250 mm and 400-450 mm depth in a 75 mm steel casing core. The samples were weighed, then dried for at least 24 hrs at 105°C and then weighed again. The bulk density of the samples was taken as the oven dried mass divided by the core volume. The bulk density of the 0-50 mm and 50-100 mm depth soil samples was calculated according to the clod method for determining bulk density from Carter (1993). The samples were weighed, oven dried for 24 hours at 105°C and weighed again. The samples were wrapped tightly in plastic wrap so that moisture was prevented from infiltrating the

sample. The samples were then placed in a known volume of water and the displacement determined by measuring the volume before and after. The bulk density was then calculated by taking the oven dried weight of the sample divided by the volume of water the sample displaced.

Bulk density of manure pack at Eston Feedlot (modified from White, 2006)
Bulk density tests were conducted on twenty 50 mm lengths of undisturbed wet manure pack samples in a 75 mm diameter steel casing core. Samples were weighed, oven dried for 24 hours at 65°C and then weighed again. The volume of the core was determined and the bulk density of the samples was then calculated according to the core method for determining bulk density as described by Carter (1993). The bulk density of the compacted layer of the dry manure pack was calculated according to the clod method for determining bulk density from Carter (1993).

Drainage characteristics of wet manure pack samples (modified from White, 2006)
Undisturbed manure cores (75 mm steel casing, 100 and 200 mm long) were taken of moisture manure pack. The drainage characteristics of the wet manure pack samples were then determined from the following procedure: the manure cores (of 100 and 200 m length as contained in its steel sampling sleeve) had plastic wrap placed over the top to prevent evaporation of water and nylon mesh placed over the bottom to prevent loss of material. The core was weighed and then placed in a water bath for 48 hours to saturate. The water level in the bath was kept at a constant depth for the entire 48 hour period (75 mm for the 100 mm length cores and 150 mm for the 200 mm length cores). Finally, the core was removed from water bath, weighed, and placed in a sand bath at a suction of 200 mm for seven days and then weighed again. These values were finally used to calculate the drainage retention properties of the manure samples as volumetric moisture content.

Volumetric moisture content of dry granular manure layer (modified from White, 2006)
Five samples of the dry loose granular manure pack taken from each pen were placed in aluminum tins, weighed, then dried for 24 hours at 65°C and weighed again. Fifty mm increments on a 75 mm diameter, 300 mm height clear PVC column were marked and then nylon mesh was wrapped around the base. The sample was then "poured" into the column to between 70 and 95 mm height, tapping the sides to settle the sample. The column, sample, and nylon mesh were then weighed and plastic wrap loosely placed over the top of the column to prevent evaporation of water. The column was placed in a water bath for 48 hours to saturate and the water level in the bath was maintained at a depth of 50 mm. Afterwards the column was then weighed.

Saturated hydraulic conductivity of manure samples (modified from White, 2006)
The saturated hydraulic conductivity of the wet manure pack and the manure/soil interface samples was measured in the laboratory using the falling head method on undisturbed samples. The undisturbed samples were taken with a 75 mm diameter, 300 mm long steel cores that were cut on a band saw into 50 mm lengths. The surface in contact with the band saw was then "roughened" with a box cutter to ensure that any

manure pores were not sealed by the cutting. The manure in the cores was then saturated for 24 hours prior to testing. A layer of nylon mesh was added on top and bottom to prevent loss of sample. The weight of the sample was then recorded (wet weight).

The saturated sample was connected through tubing filled with air-free distilled water to the selected stand-pipe tube which had been filled to slightly above the chosen starting head. For the start of the test, water was allowed to fall in the stand-pipe tube, and thence through the sample. The time required for it to pass the successive calibration marks on the tube was recorded. The tube was then refilled with water and the test repeated three more times for each sample. The drop in water level within the tube over a measured time interval was used to calculate the saturated hydraulic conductivity. The hydraulic conductivity of the samples was calculated using the following equation from Jury et al. (1991):

$$K = \left[\frac{A_1 \bullet L}{A_2(t_2 - t_1)}\right]^{\ln\left(h_1/h_2\right)} \tag{3.3}$$

Where:
K = hydraulic head in cm/s
A_1 = area of tube (πr^2) in cm^2
A_2 = area of soil sample in cm^2
t_2-t_1 = elapsed time in s
h_1 = value of hydraulic head at t_1
h_2 = value of hydraulic head at t_2

Lab hydraulic conductivity tests for the compacted manure layer of the dry manure pack and undisturbed soil samples were conducted on clods held in a PVC cylinder wax mold. The sample was placed in a PVC ring and the void area surrounding the sample was filled with wax. The samples were placed in a water bath for 24 hours and then subjected to a falling head permeameter test. Each sample had three replications. The saturated hydraulic conductivity of the sample was calculated using Equation 3.5.

Repacked manure columns

To more accurately determine the properties of saturation, drainage, infiltration, and evaporation from a manure pack we packed field moist manure into PVC columns (Fig. 3.8). The columns are 100 mm inside dia by 250 mm high. A 20 mm coarse sand was put on the bottom. A wire mesh screen on top and bottom of the sand layer prevented loss of materials. Feedlot manure, collected in July, about 3 months after pen cleaning, was used. The manure had a small amount of straw (less than 10% by mass) and no evident soil content. Six columns were packed with field moist manure (0.49 kg/kg, wet basis such that the average bulk density was 477 kg/m^3. Packing occurred in approximately 50 mm layers using a 20 mm dia plastic dowel with the same number of blows per layer. The final thickness of the manure was 200 mm.

The columns were weighed; empty, with dry sand (the volumetric saturation of the sand packed as such was measured to be 0.37 m^3/m^3), and with field moist manure. The columns were saturated from the bottom up for 24 hours then weighed for saturation.

The columns were allowed to drain for 24 hours then weighed for drainage. After drainage plastic wrap was used to hold 30 mm of water ponded on top of the manure surface. The plastic wrap was removed and the time it took the 30 mm to infiltrate was timed. The amount of water that drained out the bottom was also measured. This was repeated 3 times allowing about one hour for drainage for each trial.

After rewetting by infiltration and drainage the columns were allowed to dry in a fume hood so as to determine the drying rate. Two additional columns, filled with water and saturated sand to the same depths as that of the manure, were also in the fume hood. All columns were weighed daily. The water column had water added daily so that the surface was the same height as the manure columns. During drying the manure was not disturbed.

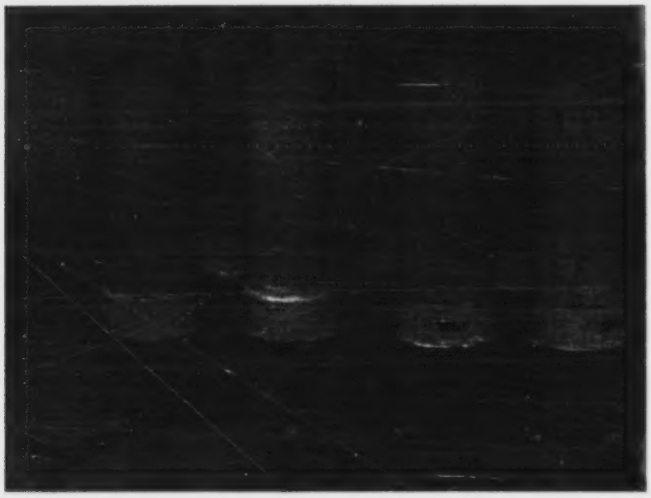


Fig. 3.8. PVC columns used for manure hydrologic properties

Absorptive abilities of manure

To determine the amount of water that manure can absorb, manure at various moisture contents, were placed in contact with a water surface. This test used small clods or loose manure granules, collected in small cores (75 mm dia by 10 mm high with a fine mesh screen) such that the bottom was in contact with a water surface (about 1 mm deep). The samples were weighed before wetting, after wetting and after oven drying (at 60°C). The purpose was to see the amount of water that could be absorbed and to see if initial moisture content affected the saturated (absorbed) moisture.

Rate of drying of disturbed manure pack

We simulated drying within a disturbed manure pack by preparing a 50 mm deep manure pack within open 400 or 600 cm^2 plastic trays placed in a fume hood. Field moist manure, obtained from active feedlots, were saturated to about 0.75 m^3/m^3 and stirred to thoroughly mix the water and manure. The trays were left in a fume hood and allowed to dry with daily stirring to mimic heavy or light disturbance by cattle. Heavy disturbance involved completely turning over and mixing the manure regardless of the moisture

content, light disturbance involved compaction and light surface turnover (about ¼ of the surface) with a 20 mm plastic dowel. One tray, with just water, was filled to the same height as the manure and served as a control. The water level in this tray was refilled daily. We repeated this experiment twice; once in 2005 using manure collected at the end of the summer (bulk density of about 450 kg/m^3) and once in 2006 using manure collected at spring time. The manure collected in spring 2006 (bulk density of about 480 kg/m^3) appeared to have some amount of soil mixed in.

3.4 Theoretical Development

Introduction

Equations for potential and actual evaporation and rainfall runoff, were used to represent various measured and unmeasured hydrological components. These equations were then utilized in a daily manure pack water balance model to determine daily moisture storage and runoff amounts given daily climate conditions for rainfall. The resulting model is applicable for the rain season, April 1 to Oct 30. Model calibration, of fitting parameters, were done using measured laboratory and field properties. Where possible the model was validated using different sets of field data.

Once the daily runoff model was developed it was then applied using long term (1940-2005) daily climatic data from 27 different locations within the agricultural region of Saskatchewan. The climatic data (daily minimum and maximum temperature and daily precipitation) was from Environment Canada. Missing data was filled in using data from nearby climate stations. The long term data enabled development of frequency-intensity equations (i.e., 1-25, 1-50, 1-100 year return periods) based upon the Gumbel distribution. Frequency-intensity equations were developed for 24 hr and seasonal rainfall and runoff events for each of the 27 locations. From the climatic data set for southern Saskatchewan and that determined from the model; rainfall, runoff, and storage pond depth maps were produced for different return periods (ranging from 1 in 10 years to 1 in 100 years), with the use of interpolation and mapping software.

Determination of Evaporation

Daily potential evaporation was determined by equation 3.4 For the Canadian Prairies this equation is slightly more accurate than that of the Hargreaves method and is explained further in the publication by Maule et al. (2006):

$$ET_t = 0.134(T_{max}-T_{min}) + 0.0109\,T + 0.708\;\Delta R_a - 0.669, \qquad (3.4)$$

Where ET_t is potential evaporation (mm/d)

T_{max}, T_{min} is daily maximum and minimum temperatures (°C)

T is daily mean temperature (Tmax + Tmin)/2, (°C)

Δ is slope of the saturation vapor pressure-temperature curve at T(kPa °C-1) :

$$\Delta = \frac{2504 \exp((17.27\,T)/(T + 237.3))}{(T + 237.3)^2} \qquad (3.5)$$

R_a is extraterrestrial radiation, mm d^{-1} as described in ASCE (2005)

Runoff: SCS Curve Number Procedure

Theory

The runoff model utilized in the final report is based upon the SCS curve number procedure (SCS, 1972) as described in SWAT Theoretical Documentation (SWAT 2005). SCS curve number procedure and our application procedures are detailed here.

The SCS curve number method was developed to provide daily runoff estimates from precipitation under varying land use and soil types:

$$RO = \frac{(P - 0.2S)^2}{(P + 0.8S)} \tag{3.6}$$

where RO: is runoff, mm

P is daily rainfall, mm

S is the retention parameter that changes depending upon soil, slope, and changes in soil water content and may be defined as:

$$S = 25.4\left[\frac{1000}{CN} - 10\right] \tag{3.7}$$

where CN is the curve number for the day and is referred to as the SCS curve number.

The SCS curve number is a function of the soil's permeability and antecedent soil moisture. The permeability of a soil is affected by texture, organic matter and compaction. Feedlot floors are compacted soil mineral material and open earthen feedlots are commonly assigned a CN value of 90, which means it has a high runoff potential, as compared to an agricultural soil which can vary between 60 and 75 for a good quality productive soil.

The antecedent soil moisture affects the CN; the wetter the soil, the lower S and thus the higher the CN. Towards this we utilized a series of equations that defines antecedent moisture conditions (SWAT 2005):

I dry (also referred as wilting point)

II average moisture

III wet (field capacity)

The curve numbers for moisture conditions I and III are calculated by:

$$CN_1 = CN_2 - \frac{20\,(100 - CN_2)}{(100 - CN_2 + \exp[2.533 - 0.0636(100 - CN_2)])} \tag{3.8}$$

$$CN_3 = CN_2 \exp[0.00673\,(100 - CN_2)] \tag{3.9}$$

where CN_1 is the moisture condition I curve number, CN_2 is the moisture condition II curve number and CN_3 is the moisture condition III curve number. As we wished the SCS curve number to account for daily changes in antecedent moisture the following set of equations were used (SWAT, 2005):

$$S = S_{max}\left[1 - \frac{SW}{[SW + \exp(w_1 - w_2\,SW)]}\right] \tag{3.10}$$

"where S is the retention parameter for a given day (mm), S_{max} is the maximum value the retention parameter can achieve on any given day (mm), SW is the soil water content of the entire profile excluding the amount of water held in the profile at wilting point (mm H_2O), and w_1 and w_2 are shape coefficients". The maximum retention parameter value, Smax, is calculated by solving equation 3.7 using CN_1.

"The shape coefficients are determined by solving equation B7.5 assuming that:

1) the retention parameter for moisture condition I curve number corresponds to wilting opint soil profile water content,
2) the retention parameter for moisture condition III curve number corresponds to field capacity soil profile water content, and
3) the soil has a curve number of 99 (S =2.54) when completely saturated."

$$w_1 = \ln\left[\frac{FC}{1 - S_3\, S_{max}^{-1}} - FC\right] + w_2\, FC \tag{3.11}$$

$$w_2 = \frac{\left[\ln\left[\frac{FC}{1 - S_3\, S_{max}^{-1}} - FC\right] - \ln\left[\frac{SAT}{1 - 2.54\, S_{max}^{-1}} - SAT\right]\right]}{(SAT - FC)} \tag{3.12}$$

where FC is the amount of water in the soil profile at field capacity (mm H2O), S3 is the retention parameter for the moisture condition III curve number, Smax is the retention parameter for the moisture condition I curve number, SAT is the amount of water in the soil profile when completely saturated (mm H_2O)."

Given the daily loss or gain of moisture from the soil or the manure pack, S is adjusted accordingly with the equations 3.8 to 3.10. Each day CN is calculated from S:

$$CN = \frac{25400}{(S + 254)} \tag{3.13}$$

Application of Theory to Beef Feedlots

The above equations were developed for soil conditions. A manure pack is a different material and lacks the porous and capillary nature of that of soil, and has a high organic content and continuous disturbance by that of cattle. To help with the adjustment of factors we considered published CN values from previous feedlot studies and some of our own measurements. As based upon literature values (next section) and our own measured values (Tables 5.1 and 5.2 in main report) we found that the following values produced the most suitable range of CN values with an upper limit of 97 representing very wet conditions and 57 very dry.

Depth of manure pack, 50 mm
Permanent wilting 0.05 m^3/m^3, or 2.5 mm
Field capacity 0.50 m^3/m^3, or 25 mm
Saturated 0.75 m^3/m^3 (change in bulk density at this stage), or 37.5 mm

Using these values we then calculated the coefficients w_1 and w_2 (Eqs 3.11 and 3.12) as 5.32 and 0.170 respectively. From these values and the amount of water in the manure pack, SW, the amount of storage before the onset of runoff, S, can be calculated using Eq. 7.5. From S the CN value can be calculated using Eq. 3.13.

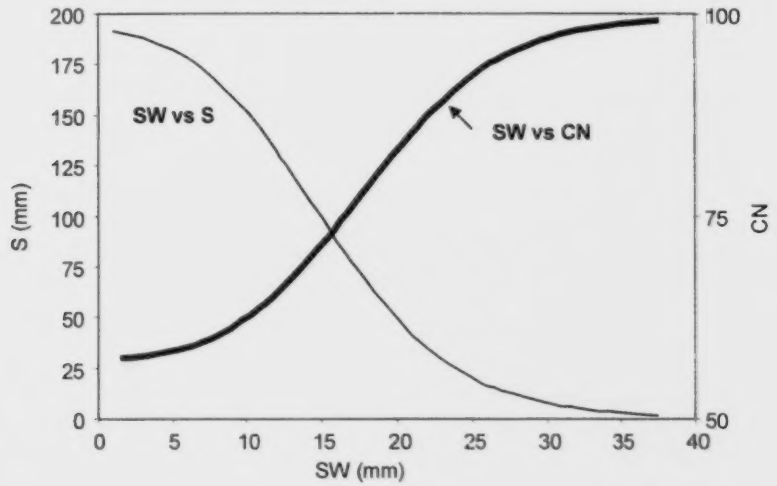


Fig. 3.9 Relationship between manure pack moisture content (SW), runoff retention factor (S) and runoff curve number (CN) as calculated from equations 3.6 to 3.13.

The relationship between SW and CN can be represented by:

$$CN = 61.01 - 0.0044\,SW^3 + 0.228\,SW^2 - 1.67\,SW, \text{ for } SW>3 \text{ and } <31.$$

For SW values ≤ 3 mm, CN=57 and for SW values ≥ 31mm CN = 97

Given daily additions and losses of water SW can be calculated daily:

$$SW_j = SW_{j-1} + P_{rj} + P_{cj} - AE_j - RO_j \qquad (3.14)$$

where 'j' is the current day, and 'j-1' is the previous day

Runoff of the current day (RO_j) is determined from equation 3.8 using added waters (rain, P_{rj} and cattle excreted water, P_{cj}) of the current day with the S value calculated at the end of the previous day (S_{j-1}).

Climatic Data and Calculation of Return Periods

Determination of rain and evaporation maps for southern Saskatchewan was determined using 27 locations (Fig. 3.10). Data for these locations are from Environment Canada (2007b), National Climate Data and National Archive (http://www.climate.weatheroffice .ec.gc.ca/climateData/canada_e.html). Stations that had continuous daily data (precipitation and minimum and maximum temperature) from April 1 to Oct 31, from 1940 to 2005 were selected. All data was reviewed for outliers and missing data. Most stations had some missing data (generally less than 1%) and a few up to 10%. In almost all cases the missing data was obtained by using nearest station for the period. In a few

cases where the missing data was one day, it was filled by averaging values from adjacent days.

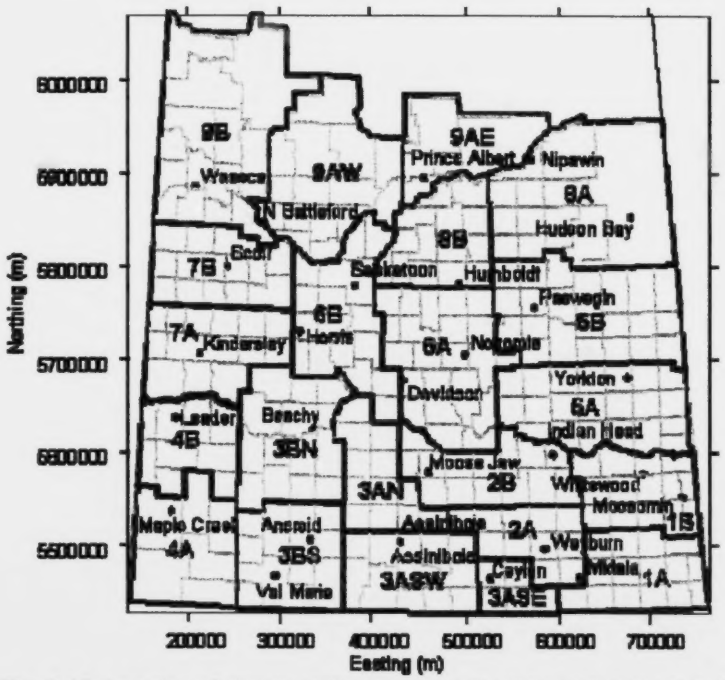


Fig. 3.10. Location of climate stations used to for daily meteorological data, 1940-2005, April 1 – Oct 31. Areas outlined in gray are Rural Municipalities. Larger areas in heavy outline with bold identifiers are Crop Districts

Rainfall or runoff intensity return periods, e.g., maximum amount to occur within 5, 10, 25, 30, 50, and 100 years were determined using the Gumbel distribution. This is done by finding the maximum value that occurs within each year. Calculating the mean and strandard deviation for all of these values (for our data set this was from 1940 to 2005 inclusive), then solving the Gumbel expression for K (standard deviations above the average maximum annual rainfall or runoff)

$$K = -0.78 [0.577 + \ln(\ln(Tr/(Tr-1)))], \quad (3.17)$$

Where; Tr is the desired return period in years

Then to find the projected amount of the extreme rainfall the following equation is used:

$$R_T = R_{av} + K R_s, \quad (3.18)$$

Where: R_T is the rainfall amount expected for a 1 in Tr year event, R_{av} is the average annual extreme rainfall and R_s is the standard deviation of the annual extreme rainfall events (EAS 345 Hydrology, http://www.sci.ccny.cuny.edu/~stan/E345_L13.doc).

For example: for Saskatoon daily precipitation (April 1 to Oct. 31) for the years 1940 to 2005, the average and standard deviation of the maximum annual values (e.g., for 1940

the maximum 24 hr value was 23.6 mm, 1941 21.6 mm, 1942 38.4 mm, ….etc.) is 35.8 an15.5 mm respectively.

K for 25 year return period is

$0.78\ [0.577 + \ln(\ln(25/24))] = 2.04$

and the projected 1 in 25 year 24 hour rainfall is:

$R_{25} = 35.8 + 2.04\ (15.5) = 67.4$ mm

4. Manure Pack and Feedlot Floor Results

4.1. General Feedlot Pen Floor Conditions

Introduction

The feedlot pen floor begins at the mineral surface. On this mineral surface is the manure and straw layer. Several layers on and within the mineral floor can be recognized (Fig. 4.1):

1) Physically unaltered mineral soil material below 300 mm in depth. This is soil material that although may have some higher dissolved nutrients has not been disturbed or compacted by the cattle nor undergone anaerobic conditions;
2) Physically altered mineral layer from the mineral surface to about 50 mm in depth. This layer is black from anaerobic conditions, may have higher organic matter content due to physical mixing or clogging of organic particles. It is usually very compacted and also may be very hard when dry due to salts. During very wet conditions this layer and deeper may be mixed in with manure by cattle;
3) Manure layer on top of the mineral surface. The physical properties (surface roughness, density, waterholding capacity, and hydraulic conductivity) of the manure layer will be dependent upon age of manure, moisture content, and amount of mixed straw and mixed soil.
4) Straw layer on top of mineral or manure surface. Straw is added to pens for animal bedding especially during winter time. The accumulation of this can result in mounds up to 1 m in depth. Manure can be mixed in with this and the mound can be spread about the pen by the cattle.

Other processes can alter and rearrange the material within the pen. Freezing conditions during winter will result in little mixing and decomposition of material. Subsequent thawing in spring will result in a very liquid surface with runoff and excessively muddy conditions. Low spots in the pen can collect runoff waters and manure present in these areas can be mixed into a slurry. Under wet conditions cattle can mix the manure/straw into the soil layer. If water bowls and feed troughs do not have a concrete apron then the surrounding area can also become very wet and mixed. Mounding of manure and straw by equipment can result in animals being concentrated in those or other areas.

All of the above conditions can affect the occurrence and amount of runoff given a rain event.

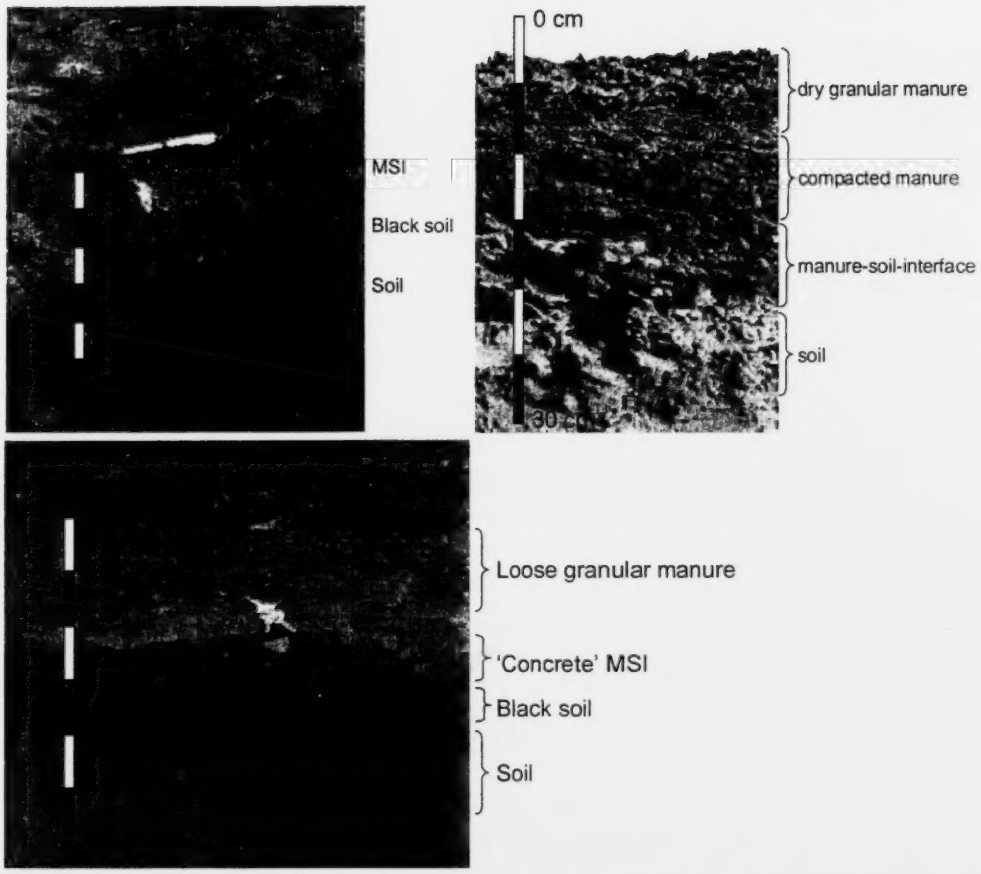


Fig. 4.1. Photographs of manure soil layers. Vertical bar in photos is about 300 mm long. **Upper left photo** is from a moist feedlot that was recently scraped – soil is soft and a manure-soil-interface (MSI) layer remained on top of a soft black soil layer. **Upper right photo** is from a dry feedlot and comprises 4 layers; an upper granular, then a brittle dense manure layer, then a manure soil interface that was also very hard, then the underlying soil layer – this feedlot was only several years old. **Bottom photo** is from an older feedlot (25 years) in sandy material – a concrete-hard upper layer of sand, organic matter covered a thin black layer.

Feedlot Manure Pack

The manure pack generally consists of manure under various stages of decomposition. Straw left over from winter bedding can form a considerable part of it unless removed during spring scraping. At one lot it was observed that the straw mound built up over winter was left in the center and the wet manure scraped away after the surface ice and snow had melted. Generally by the end of the summer there is little straw remaining, if there has been a mid summer scraping. The manure pack, not including the straw mound, will vary in thickness from a few cm to more than 30 cm depending upon pen location and frequency of cleaning. It can also vary in consistency dependent upon moisture conditions and the degree of mixing with soil and straw. Under very dry conditions the bottom part of the manure pack, if thick, or the entire manure pack, if thin, will become

compacted and very hard. It can form a hard brittle layer (0 to 50 mm layer in Table 4.1, Fig. 4.2) that has a very low hydraulic conductivity. Similarly when dry it can also form a loose granular dusty layer (Table 4.1). As the manure pack wets up it goes from a granular brittle layer to a moist moldable layer, and finally to a slurry. If cattle are active then the manure will stirred into a slurry form that will flow.

Table 4.1. Feedlot manure pack and soil bulk density, saturated volumetric moisture content, and saturated hydraulic conductivity.

Location to mineral surface (mm)	n	bulk density (kg/m^3)	saturated moisture (m^3/m^3)	Saturated hydraulic conductivity cm/s	Comments
+	20	233	NA	NA	mostly straw with some manure
+	31	455	0.58	NA	misc manure pack
+	19	419	0.07	NA	dry loose manure
+	19	479	0.51	NA	moist manure pack
+	13	443	0.67	NA	very wet slurry manure
75 to 220	5	200	0.84	2.85E-03	wet manure & straw
0-100	17	427	0.71	3.63E-04	manure & straw maybe some soil
0-50	7	783	0.44	4.97E-06	Compacted dry manure
-25 to 25	6	966	0.53	3.03E-06	interface
-50 to 0	11	1653	0.31	4.84E-06	Soil 0-50 mm depth
-100 to -50	12	1596	0.38	3.33E-05	Soil 50-100 mm deep
-200 to -100	7	1472	0.41	6.57E-06	Soil 100-200 mm deep
-300 to 200	18	1405	0.43	3.66E-05	Soil 200-300 mm depth
-500 to -300	10	1508	0.42	3.26E-05	Soil 300-500 mm depth

Positive surface values refers to above mineral surface set at 0 cm. Thus '+' refers to manure and straw packs whereas '-' refers to depth beneath the mineral surface within the soil.
With exception of the 'misc. manure pack' all values are from 75 mm dia by 50 mm high cores. 'Misc. manure pack' are from 100 and 200 mm long cores taken through a deep manure pack with some straw. 'n' is number of samples. Samples are from three study feedlots.

A typical bulk density of the manure pack, with no soil and little straw, is between 400 and 480 kg/m^3 with little difference whether it is very dry, moist or a slurry (Table 4.1). Straw packs, with some manure, average about 230 kg/m^3 ($\pm$ 52 as 1 standard deviation) with higher values indicative of greater manure content and/or greater decomposition. Under wet conditions the cattle can mix manure into the top part of the soil resulting in higher bulk densities (600 to 900 kg/m^3) and much lower hydraulic conductivities. Generally the manure pack will have saturated hydraulic conductivities of at least 2×10^{-4} cm/s and higher unless it has been compacted or mixed with soil. Straw packs will have much higher hydraulic conductivities.

A moist manure pack has several features that are important to runoff; it has a ability to absorb and retain moisture, it has a high hydraulic conductivity (relative to the underlying soil), and in a moisture state it is moldable and has a very rough surface that can serve to detain ponded water. As a manure pack dries it can become compacted and create a smooth layer that has a high potential for runoff due to its very low hydraulic conductivity. Similarly if the manure pack is very wet and approaches a slurry state, it will have a smooth surface and its saturated condition does not allow for any further water absorption.

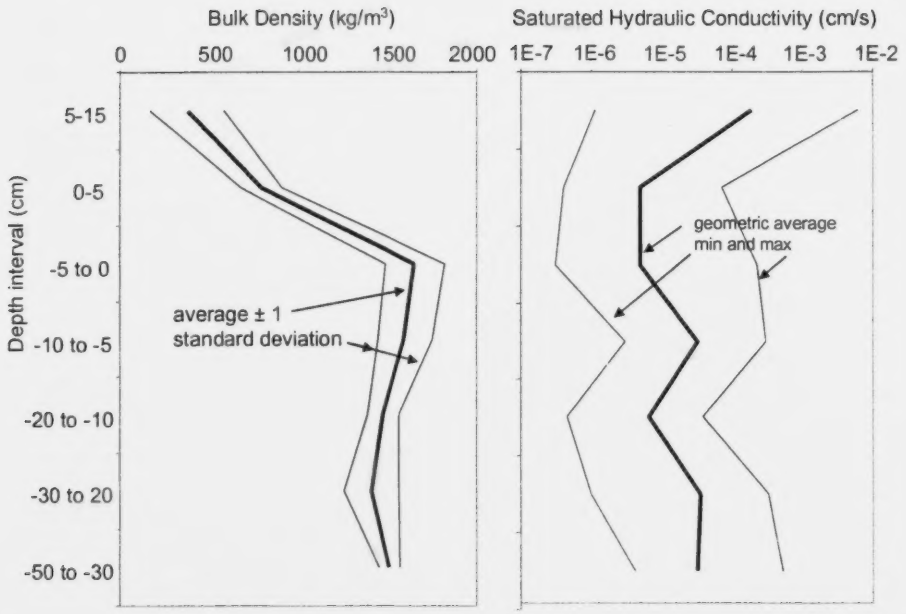


Fig. 4.2. Bulk density and saturated hydraulic conductivity with depth from within manure pack to within the soil. Positive depth interval values is manure pack above the mineral soil surface, negative values are below minerals soil surface, zero is the mineral soil surface. Values are those expressed within Table 4.1.

Mineral soil

The feedlot floor is composed of mineral soil. This soil material underlies the manure and becomes altered: due to salts and nutrients that leach from the soil into the manure; due to mixing of organic matter; due to anaerobic conditions created by the wet manure layer; and due to compaction. Previous studies (Mielke and Mazurak, 1976; Southcott and Lott, 1997; Kennedy et al., 1999; McCullouogh et al., 2001) have shown that due to this the top part of the soil becomes greatly reduced in permeability. This is shown by the lower hydraulic conductivities in the upper 50 mm of the soil (Table 4.1, Fig. 4.2).

Due to the compacted status of the feedlot mineral soil and its low hydraulic conductivity, it is assumed that downward seepage is too low during wet conditions (less than 1 mm per day) to have a measurable effect upon the reduction of runoff events.

4.2 Laboratory Determined Manure Pack Properties

The manure pack intercepts precipitation and thus regulates that of infiltration and runoff. The manure pack thickness and ability to absorb water and it's ability to release water by gravitational drainage or by evaporative drying between rain events are key towards controlling runoff occurrence and amount. These parameters will be affected by the manure pack composition of manure, straw, and soil, and degree of decomposition. To test these parameters we utilized laboratory tests conducted upon feedlot manure pack samples.

How much water can a manure pack hold at saturation?

Manure with a small amount of straw (less than 10% by mass) and no evident soil content, and was from a feedlot that had been cleaned 2 months previous to sampling (late July) was packed moist (about 0.49 kg/kg wet basis) into 6 replicate columns such that the average bulk density was 477 kg/m^3 (Table 4.2) before saturation. A 20 mm coarse sand layer with screens on top and bottom of the sand was at the column bottom. The columns (100 mm dia. by 220 mm of manure) were saturated from the bottom up (Fig. 3.8). At saturation their moisture content averaged 0.69 m^3/m^3, 0.59 kg/kg (wet basis), or 1.44 kg/kg (dry basis). Thus for every 100 mm of manure pack at saturation (without disturbance), 69 mm of water occurred or a kg of dry manure held 1.44 kg of water. There was a negative relationship between bulk density and mass moisture content ($r^2 = 0.72$). Some observable swelling of the manure surface occurred at saturation.

Another test put small clods or loose particles of manure loosely held in small cores (75 mm dia. by about 10 mm high) such that the bottom part was in contact with water. The manure was at different initial moisture contents ranging from 0.10 to 0.60 kg/kg (wet basis). Final moisture contents averaged 0.62 kg/kg (wet basis) with 0.70 kg/kg the highest. Some slight swelling of dry samples were observed.

How much water can a manure pack hold after gravitational drainage?

The columns of manure, about 220 mm high, were allowed to freely drain, after being saturated. Their average moisture content after drainage (3 hours) was 0.61 m^3/m^3, 0.56 kg/kg (wet basis) or 1.27 kg/kg (dry basis). Seventy percent of the waters that drained were released in the first 10 minutes and the last 4% between 2 and 3 hours. The drained mass moisture content was positively correlated to saturated mass moisture content ($r^2 = 0.98$). The total volume of water that drained was negatively correlated to bulk density ($r^2 = 0.80$). Thus for every 100 mm of saturated manure pack 8 mm of water was removed by drainage.

Does manure pack infiltration rate vary with time and with trial?

The same columns after drainage had occurred had 30 mm of water ponded on top and held in place by plastic wrap. Upon removal of the plastic wrap the time it took for the 30 mm to infiltrate into the surface was timed. The amount of water that drained out the bottom was also measured. This was repeated three times within about 3 hours allowing for 1 hour of drainage between each test. The purpose was to measure infiltration rate and to see whether it varied with the stage of wetness and with the amount of infiltrated

water. The average infiltration rate of the first trial was 23.9 mm/min (ranging between 2.1 and 72 mm/min) and reduced to 8.4 mm/min and 8.5 mm/min by the second and third trials. There was a negative correlation between bulk density and infiltration rate. Saturated wet mass moisture content was positively correlated ($r^2 = 0.87$) and bulk density was negatively correlated ($r^2 = 0.76$) with the first trail infiltration rates.

Rate of drying of undisturbed manure pack

Evaporative drying of the manure columns were allowed to see how much drying occurred relative to a water surface and a saturated sand column. How fast manure dries between rains will control how much water can be absorbed for the next rainfall. After the columns had finished draining from the previous tests they were stored in a fume hood with the air flow left on. Two other columns were prepared, one with just water, set to the same height as the manure surface and another with a saturated sand. The average rate of water evaporation (potential evaporation) throughout 20 days of testing was 6.9 mm/d. During the first 18 hours the manure columns were equivalent to potential rates, but by 44 hours had dropped to 3.9 mm/d, by 92 hrs to 2.0 mm/d, by 198 hrs to 1.3 mm/d and by 486 hrs to 0.8 mm/d (Fig. 4.3). Disassembly of a manure column after 293 hours indicated a very dry 50 mm cap underlain by moist manure, while the bottom of the column was very wet. When the top layer of manure dried it shrank and pulled away from the sides – this would have allowed for a greater evaporation rate from the underlying wet manure. Disassembly of manure columns after two months within the fume hoods found very wet conditions in the bottom 100 mm of the column. Drying is very slow in deep manure packs. The sand column maintained much higher rates of evaporation, at 365 hours it was 6.1 mm/d (Fig. 4.3) as compared to potential evaporation of 6.8 mm/d. Likely the porous capillary network of pores within the sand medium allowed transport of water to the evaporating surface where as manure did not allow such capillarity.

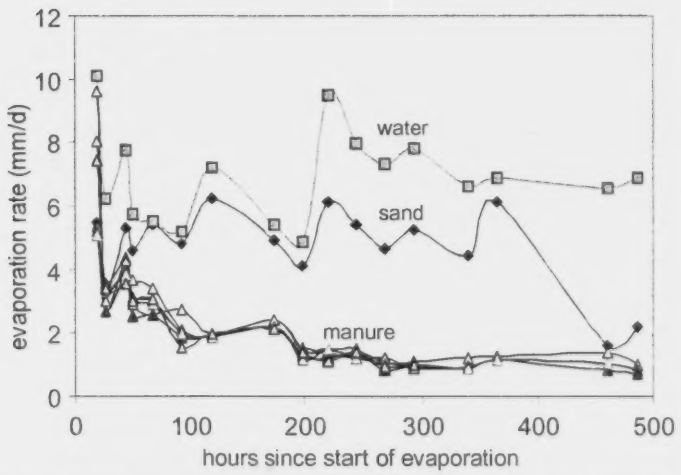


Fig. 4.3. Evaporation rate of undisturbed manure within 220 mm PVC columns

Rate of drying of disturbed manure pack

We simulated drying within disturbed manure pack by preparing a 50 mm deep manure pack within open 400 or 600 cm^2 plastic trays (Fig. 4.4). Field moist manure obtained from feedlots was saturated to about 0.75 m^3/m^3 and stirred to mix the water and manure. The trays were installed in a fume hood and allow to dry with daily stirring to mimic heavy or light disturbance by cattle. Heavy disturbance involved completely turning over and mixing the manure regardless of the moisture content, light disturbance involved minimum disturbance and when drier the surface was compacted with a 20 mm plastic dowel with some light breaking (simulating an animal hoof). One tray with just water filled to the same height as the manure was used as a control. The water level in this tray was refilled daily. We repeated this experiment twice; once in 2005 using manure collected at the end of the summer (bulk density of about 450 kg/m^3) and once in 2006 using manure collected at spring time. The manure collected in spring 2006 (bulk density of about 480 kg/m^3) appeared to have some amount of soil mixed in.

The average evaporation rate from the water (control) was higher in 2006 (8.9 mm/d as opposed to 6.8 mm/d) due to the test being conducted in different fume hoods between years. There was no observable difference in drying trends between heavily or lightly disturbed manure trays. The results for 2006 are summarized in Fig. 4.4. For all trays the rate of drying approximated that of the control (water) for the first 70 to 100 hours and then decreased rapidly (more rapid for 2006 test) until about 200 hours. If the relative evaporation rate is expressed against that of volumetric moisture content there is an approximate linear trend (Fig. 4.4). At moisture contents 0.50 m^3/m^3 and above the actual evaporation rate (AE/PE) from manure might be constant and related directly to that of the potential rate, however there was higher variability in the beginning and it is difficult to tell. Our fitting equation is for linearity from 0.02 to 0.69 m^3/m^3.

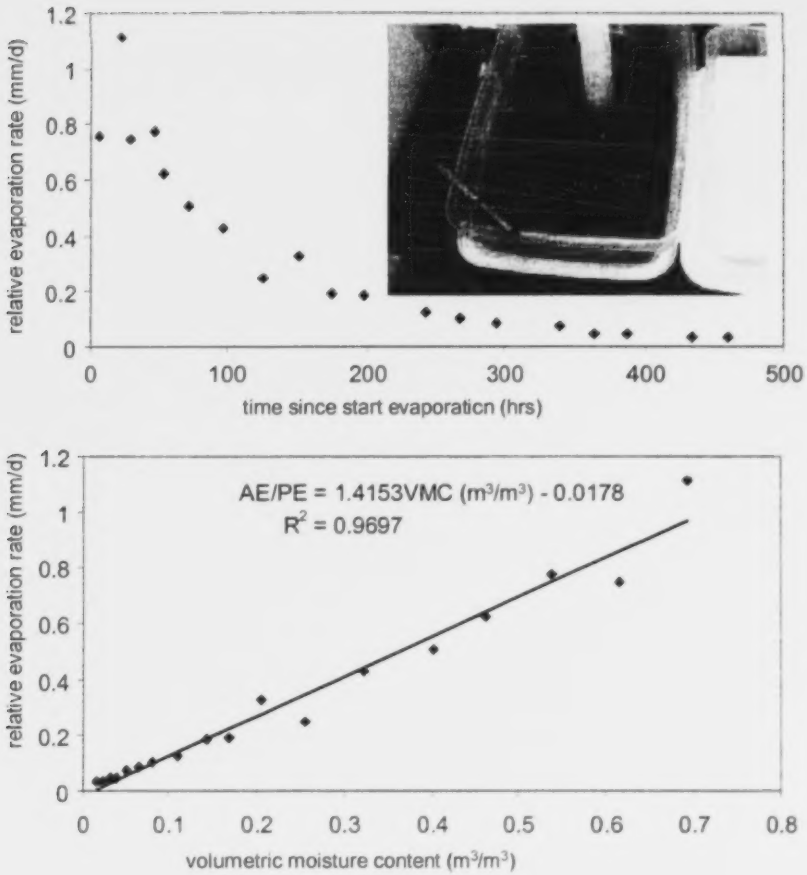

relative evaporation rate (mm/d)
time since start evaporation (hrs)
AE/PE = 1.4153VMC (m³/m³) - 0.0178
R² = 0.9697
relative evaporation rate (mm/d)
volumetric moisture content (m³/m³)

Fig. 4.4. Relative evaporation rate from manure trays vs time from initially saturated manure (top figure). Relative evaporation rate (to water) from manure trays vs manure moisture content, wet basis (bottom figure).
Each point is the average of six manure trays. Insert photo shows set up of trays in fume hood; left tray contains manure and plastic dowel (20 mm dia) used to disturb manure; right tray is filled with water. Relative evaporation is evaporation rate as measured from manure trays divided by evaporation rate of water from similar tray (average 8.9 mm/d).

Assuming that there is no difference caused by disturbance then the relationship between volumetric moisture content (VMC) and relative evaporation rate are:

$$AE/PE = 1.42\ VMC - 0.02,\ R^2 = 0.97,\ \text{for } 0.02 \text{ to } 0.69\ m^3/m^3 \qquad [4.1]$$

Manure consistency

The manure pack changes physical state dependent upon the moisture content. The physical state thus affects the runoff potential; a dry manure pack will be dusty with a smoother surface but granular with a large absorptive capacity; a moist pack will be moldable and have a very rough surface for water detention; a very wet pack will be a slurry with a smooth surface and can flow. Moisture contents above 0.68 kg/kg (wet

basis) are generally liquid and will flow on its own (Fig. 4.5, Table 4.2). Moisture contents between 0.50 and 0.62 kg/kg are plastic, deforming under pressure but retaining their shape. Within this range the manure surface is very rough. Below moisture contents of 0.50 kg/kg (wb) the manure is moist and clumpy, friable and tends towards compaction when pressure is put upon it. Below moistures of 0.30 (kg/kg, wb) the manure pack is beginning to get slightly brittle and can crumble into smaller pieces. If the moisture is less than 0.10 kg/kg (wb) then the manure pack can get very dusty.

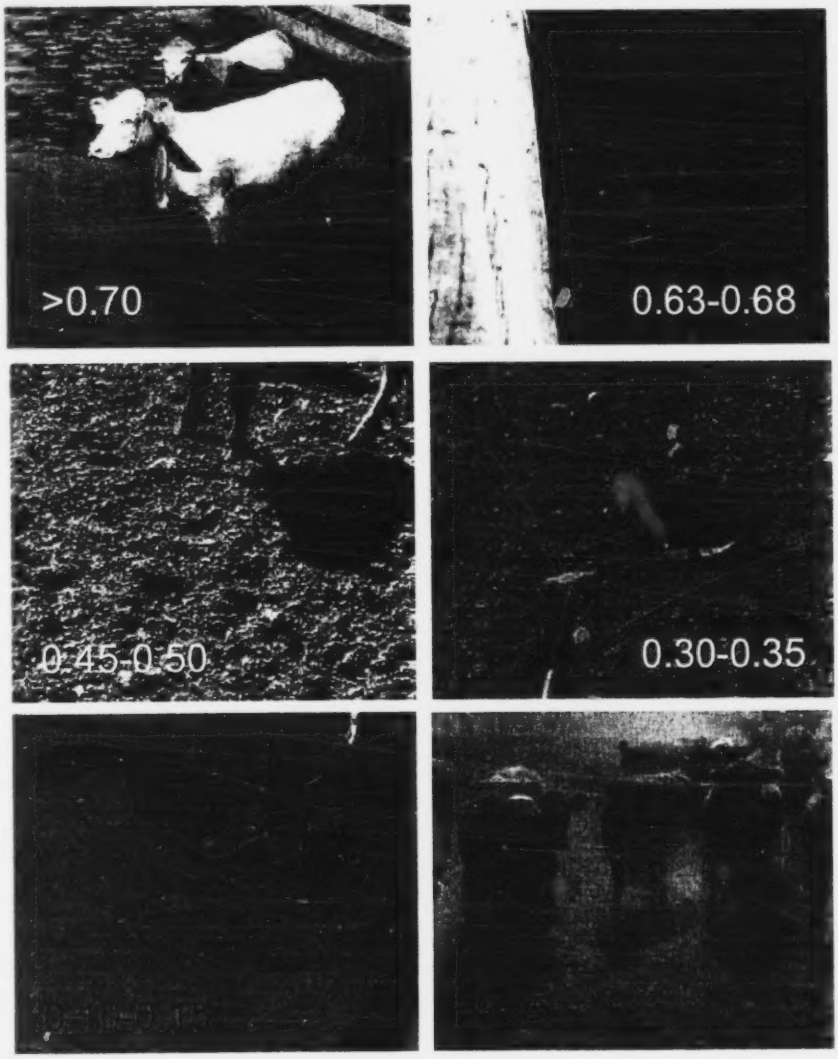


Fig. 4.5. Manure pack consistency and how it varies with mass moisture content on a wet basis (values in each photo).

Table 4.2. Physical and hydrologic properties of manure pack with moisture content

Mass moisture (kg/kg, wb)	Volumetric moisture (m^3/m^3)*	CN value†	Consistency and physical description
>0.70	>0.80	96	liquid with water on top
0.68-0.70	>0.80	96	slurry, flows under own weight, smooth surface
0.62-0.68	0.73-0.80	96	plastic to slurry; grove in manure will fill in with slight disturbance, rough to smooth surface
0.52-0.62	0.49-0.73	88-96	plastic and sticky, moist, can be molded and will retain shape, at lower moisture compaction is possible, rough surface capable of high water detention.
0.32-0.52	0.21-0.49	72-87	friable, moist can clump but breaks apart, manure can be compacted by cattle, rough surface
0.10-0.32	0.05-0.21	61-71	crumbly with some brittleness and dust at the dry end, can still feel some moisture upon touch, rough to flat surface
<0.10	<0.05	55-60	hard to break clumps by hand, hard, dusty when broken, flat surface. Manure granules can be eroded by wind.

*Volumetric moisture content calculated from mass moisture content assuming a bulk density of 450 kg/m^3 for mass moistures 0.62 kg/kg and less. Above 0.65 kg/kg dry bulk density becomes less due to particle suspension. At a moisture content of 0.70 kg/kg a bulk density of 370 kg/m^3 was assumed.
CN is Curve Number

5. Field Measurements and Model Development

5.1 Cattle Input

Given that the moisture content of excreted manure (urine and feces) is 88 % (wb) (USDA, 1999, ACFA and AAFRD, 2002) and cattle excrete about 58 kg total manure per day per 1000 kg of animal (ACFA and AAFRD, 2002) then the depth of moisture (Pc, mm) excreted is dependent upon the stocking density (Sd, m^2/hd), the animal mass (Am, kg), and the number of days (J):

$$Pc = 0.0495\ Am\ J\ Sd^{-1} \qquad [5.1]$$

At the three lots studied the size and number of cattle varied, however the stocking density was about 20-25 m^2/hd and the size was more in the 180 -320 kg range (400 to 700 lb) range and sometimes larger. Smaller stocking weight was usually at higher stocking densities. Thus according to equation 1 cattle input would range from 0.4 to 1.0 mm/d. For our model development we used a cattle input rate of 0.75 mm water per day into the pen surface.

5.2 Manure pack moisture; Measured and Modeled

Manure pack samples were taken at one to 3 week intervals during spring thru fall of 2005 and 2006 from the two Saskatoon feedlots. Mass moisture contents were measured of all the samples and for most of them, bulk densities were also taken. A manure water balance model was developed such that the moisture content of the manure pack could be predicted given the actual evaporation equation for manure (Eq. 4.1), calculated daily potential evaporation (Eq. 3.6), and measured daily precipitation.

On a daily basis the moisture inputs were:

Pr, rainfall, measured in mm/d:
Pc, cattle contributed water, assumed to be 0.75 mm/d

On a daily basis moisture losses were:

AE (mm/d) as measured with Eq. 4.1 with
PE determined from daily temperature and location parameters (Appendix B)
VMC; volumetric moisture content for a 50 mm manure pack that could vary in moisture content from 0.02 (air dry) to 0.75 m^3/m^3 (saturation)

RO, runoff in mm/d, any volumetric moisture greater than 0.75 m^3/m^3 was deemed as lost due to runoff and was removed from the manure pack. This is not runoff from the lot but seen mostly as redistribution, as runoff can occur before the manure pack reaches this moisture content.

D, drainage in mm/d, this was assumed to be 0 mm/d due to the low hydraulic conductivity of the compacted feedlot floor.

The manure pack also has a storage term, SM

SM is the amount of moisture stored in the manure pack in mm depth of water.

Thus the manure moisture balance equation is:

$$SM_j = SM_{j-1} + Pr_j + Pc_j - AE_j - RO_j \qquad [5.2]$$

where 'j' is the current day, and 'j-1' is the previous day.

The model is only for the months where the average temperature is above 0°C, April thru October, and on April 1 S is set at 52.5 mm (0.75 m^3/m^3 x 50 mm depth of manure pack) due to just completed snowmelt. Rainfall and cattle contribution for the day is lost at a rate of AE=PE until all P or PE is accounted for. Any remaining P increases S or any remaining PE decreases S as AE. The manure pack thickness was set at 50 mm. The measured manure pack varied in thickness from 0 mm, after recently scraping to as much as 300 mm. Likely 100-150 mm is a more appropriate average thickness for the summer, however for model development 50 mm provided a better fit. Generally the model shows a relative agreement of fit between measured and predicted (Fig. 5.1) as illustrated by agreement between extreme lows and high values.

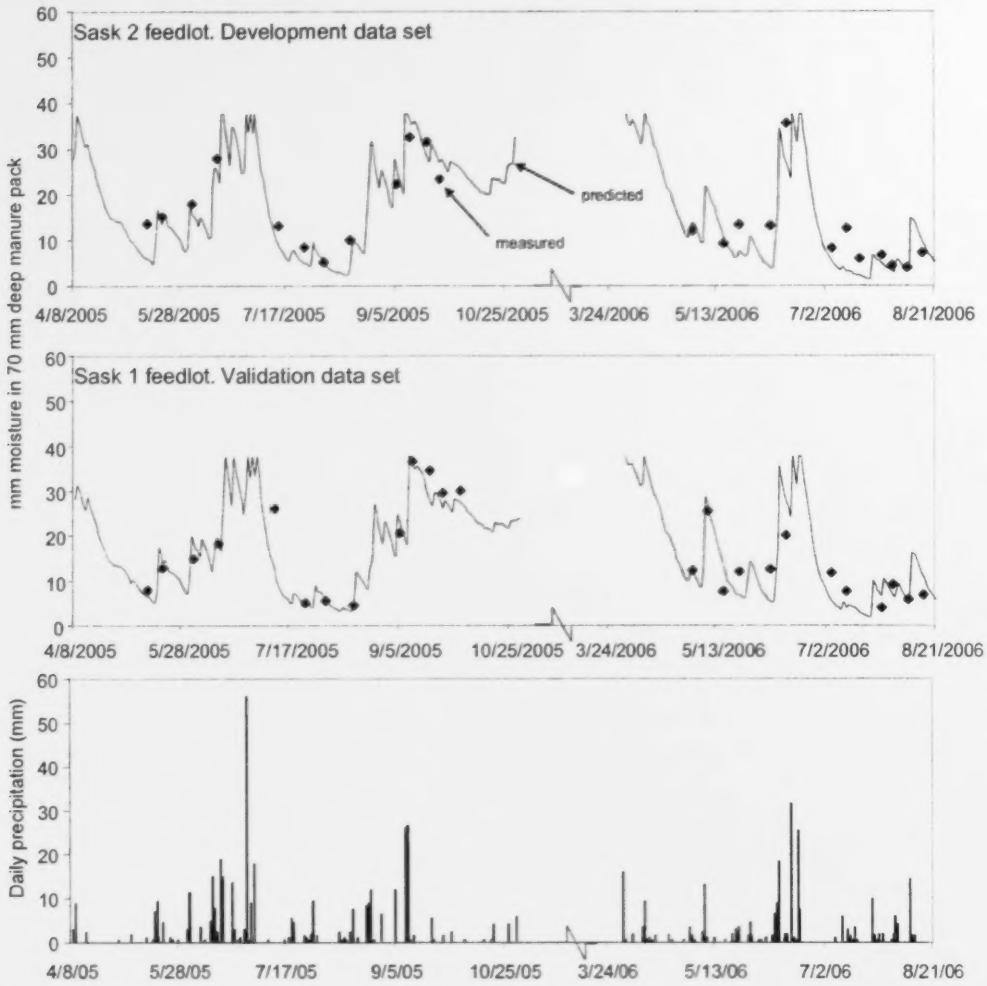


Fig. 5.1. Top two graphs are measured and predicted (Eq. 5.2) pack moisture for two feedlots near Saskatoon. Bottom graph is daily precipitation as measured at Saskatoon Airport, April 1 to Oct 31, 2005 and 2006.

The agreement between predicted (SMp) and measured (SMm) moisture of the two data sets shown in Fig. 5.1 is close to 1:1:

$SMp = 0.99\ SMm - 2.17,\ r^2 = 0.843$, for Sask 2 (model development)
$SMp = 0.88\ SMm - 0.83,\ r_2 = 0.802$ for Sask 1 (model validation)

5.3 Runoff Measurements

Although we installed runoff weirs at three feedlots we failed to record proper runoff events due to lack of runoff events during measurement period (2004 at Eston feedlot) or due to retention of runoff waters within feedlots (2005 and 2006 at the Saskatoon feedlots). From field measurements we do have the following data:

Eston recorded instances of runoff and instances when runoff did not occur. We established weirs for two feedlot pens that monitored the period of July through Oct 2004. The pens at the time had no cattle, however had a light manure pack; about 1/3 of the pen area in packed bare hard manure, about 1/3 granular dry (about 25 mm thick) and about 1/3 straw and manure slight mound, about 100 to 200 mm thick. Conditions were dry (Fig 5.2). During weir operation there were three events greater than 10 mm (13, 19, and 12 mm). Measurable runoff was only recorded from one event, 0.1 mm from the 19 mm rainfall. The manure pack could have been moist as indicated by daily light rainfalls (3 to 10 mm) during the previous six days. During the two years of observations (2003 and 2004) the only time that water was observed in the runoff ponds paralleling the feedlots were just after spring snowmelt. Runoff could have occurred and infiltrated rapidly. Due to the distance of the site (3 hour drive) monitoring was infrequent.

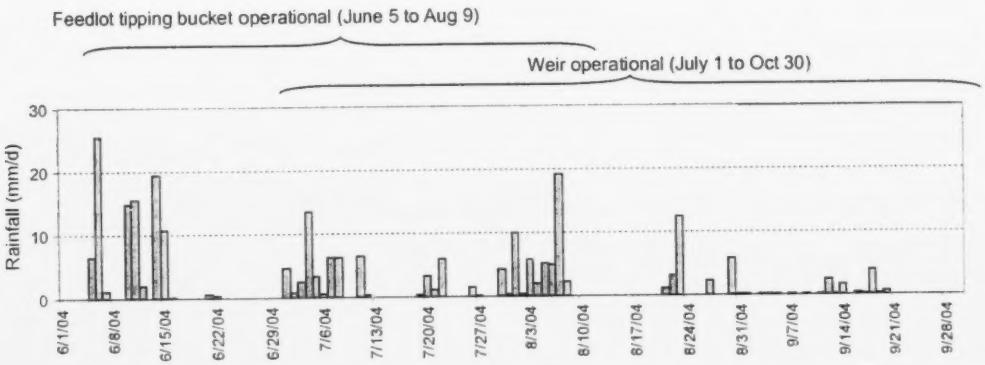


Fig. 5.2. Daily rainfall events at Eston feedlot during summer through fall 2004.

Runoff was also monitored using a rainfall simulator (Appendix B) upon 1 m^2 areas (Table 5.1). A bare hard packed manure surface produced runoff very rapidly resulting in runoff Curve Number (CN) values of between 87 and 98, whereas the dry granular surface only produced runoff for one out of three tests within almost two hours, producing a very low CN value of 39. Low summer precipitation and the lack of cattle resulted in a dry manure pack with a high water absorptive capacity.

Table 5.1. Runoff parameters from rainfall simulator tests done on natural manure pack surface under dry conditions

Test ID	Manure pack description	time to runoff (min)	rain rate (mm/hr)	total rain (mm)	total runoff (mm)	CN
MPT#2	>25 mm, dry granular	168	39	113	2	39
MPT#0	>25 mm, dry granular	>105	34	105	0	<39
MPT#1	>25 mm, dry granular	>155	34	155	0	<39
HPT#1	hard, packed, dry	1.2	36	8	4	98
HPT#2	hard, packed, dry	5.4	57	12	4	95
HPT#3	hard, packed, dry	3.0	65	11	4	95
HPT#4	hard, packed, dry	5.4	68	22	4	87
HPT#5	hard, packed, dry	6.6	51	15	4	93
HPT#6	hard, packed, dry	4.2	51	15	4	93

Weirs were established at the feedlots near Saskatoon, however runoff largely remained in the pens (Photos in Appendix C). The summers and falls of 2005 and 2006 were wetter than normal (Saskatoon Airport recorded 403 mm and 401 mm respectively whereas 1940-2006 average was 273 mm). During April 1 to Oct. 31 of 2005 and 2006 there were 23 days with rains greater than 10 mm, 8 days with rains greater than 20 mm, and three days with rains greater than 30 mm. The greatest one day rainfall was 56 mm on June 29, 2005.

Runoff from prepared manure pack surfaces under controlled rain conditions (Appendix B) showed that antecedent moisture has a strong effect upon time to runoff and the CN value with depth of manure pack only having a slight effect for wet conditions (Table 5.2). Dry conditions (granular) resulted in ponding or runoff conditions taking longer than 17 minutes to occur and CN values between 33 and 78. Moist conditions (antecedent conditions between 0.30 and 0.50 kg/kg on wet basis) had CN values between 85 and 90, while wet to slurry conditions had CN values of 90 to 95 and ponding in less than 10 seconds. The rainfall rates were relatively high (>70 mm/hr) for most tests and the moisture conditions for the moist runs were generally closer to 0.50 kg/kg wb) than 0.30 kg/kg. Depth only had slight effect if less than 75 mm in depth.

Table 5.2. Runoff parameters from rainfall simulation tests done to prepared manure pack surfaces. Manure from spring 2006 used.

depth (mm)	moisture	time to ponding (min)	time to runoff (min)	rain rate (mm/hr)	total rain (mm)	total runoff (mm)	CN
25	dry	12.0	16.8	86	40	7	78
	moist	1.0	5.8	83	52	21	85
	wet	0.5	3.2	83	50	27	89
	slurry	0.1	1.8	83	43	22	90
75	dry	NA	30.3	59	78	15	66
	moist	4.3	5.5	75	54	37	93
	wet	0.8	2.8	84	49	35	95
	slurry	0.1	2.3	92	52	37	94
150	dry	45.4	NA	79	171	8	33
	moist	3.1	12.3	69	51	28	90
	wet	0.1	7.8	63	43	28	94
	slurry	0.3	5.7	68	44	29	94
225	dry	>337	>337	55	310		

Values are averages from 2 to 4 boxes with prepared manure packs under a rainfall simulator. CN was calculated as based upon curve number method (Appendix B)
'dry' is manure pack in a granular condition 0.05 to 0.10 kg/kg, wet basis
'moist' is 0.30 to 0.50 kg/kg
'wet' is 0.50-0.60 kg/kg
'slurry' is 0.60-0.65 kg/kg

5.4 Modeling Runoff

Model Development and Testing

The SCS Curve Number Procedure (SWAT, 2005; SCS 1972) was used to predict runoff given a daily rainfall amount. The equations for this and our development of a runoff model are described in Appendix B. Model development utilized the moisture prediction model (Eq. 5.2) and a feedlot runoff data set from Lethbridge (Miller et al., 2003; 2004). The Lethbridge study monitored feedlot runoff from 1998 thru to 2002. During this period a total of 11 rainfall runoff events were recorded ranging in size from 0.1 mmm to >54 mm and producing CN values between 52 and 96. The CN runoff model we developed used daily temperature and rainfall and a manure pack depth of 50 mm. The predicted CN values relative to the measured CN values fit a slope of 0.99 with an r^2 of 0.84 (Fig. 5.3).

After development of the model using the Lethbridge data it was then tested using Eston feedlot climate data for summer to fall 2004 (Fig 5.2 shows rain data). During the periods of rainfall in which the weir was operational (July 2 to Oct) the model did not produce any runoff. The day of greatest rainfall, 19.3 mm on Aug 7, did not produce any runoff from a CN value of 67. A CN value of 72 produces trace runoff (<0.1 mm).

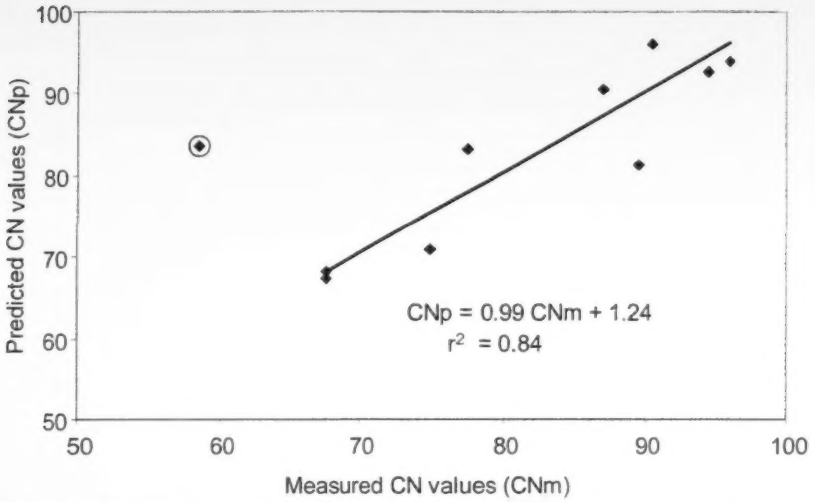


Fig. 5.3. Measured CN values from Lethbridge feedlot study (1998-2002, Miller et al., 2003; 2004ab) compared to predicted values from CN model. Circled point was not included in regression fit.

The model was also tested on the Saskatoon feedlots for which we had observations of runoff, but no quantitative measurements (Table 5.3). Rain events that produced observed runoff were generally large (>20 mm/d) and occurred when the manure pack was already wet (Sept 10 and 11, 2005). The observed manure surface followed the trends of CNp and VMCp of the model.

Table 5.3. Modeled feedlot runoff parameters and observations of manurepack on selected dates from Sask 2 feedlot. Photographs of feedlot surface for dates are in Appendix C.

Date	P mm	CNp	ROp mm	VMCp m^3/m^3	comments
5-May-05	0	69	0	0.18	dry, no excess water
13-May-05	0	64	0	0.10	dry no excess water
20-Jun-05	34	86 to 96	10.1	0.62	June 17th and 18th had 19 and 15 mm of rain. Photos show some puddles in RV pens, not excessive
29-Jun-05	73	96	32.4	0.75	Rain from June 22 to 29th with 56 mm on June 29th. June 30th shows extensive ponding in bottom halfs of feedlots
4-Jul-05	27	96	5.7	0.67	Rains on July 1 and 3rd. Photos show very wet conditions, deep manure and flooded bottom pens
13-Jul-05	0.5	96 to 70	0	0.19	10 days of dry conditions. One photo of pen with deep manure, cannot see slurry or flooded conditions
25-Aug-05	30	74 to 92	0.1	0.60	most of aug dry. 8, 9, 12 mm on Aug 23, 24, 25. RO only on Aug 25. photos show wet slurry with some flooding in bottom of pens.
29-Aug-05	0	85	0	0.38	no rain previous 4 days. photos show rough wet manure pack, no ponding visible
6-Sep-05	12	88	0	0.46	12 mm rain on Sept 5, no runoff. 5 days of drying before. Photos show rough wet manure pack, no ponding visible
12-Sep-05	53	80 to 96	20.2	0.75	26 mm and 26.5 mm of rain on Sept 10 and 11. Photos show slurry and ponding in bottom parts of pens, very deep manure. Water in ditches very little runoff through weir due to ditch plugging.
20-Sep-05	2	96 to 91	0	0.52	one week of dry weather. Photos show some very wet pens, some pens being cleaned of wet manure.
25-May-06	0	66	0	0.14	May 10 to 25 th dry with about 11 mm of rain. Photos show dry pens with granular surface
7-Jun-06	1	62	0	0.08	Very little rain in previous 2 weeks - about 9 mm. photos show dry pens with granular surface
14-Jun-06	35.8	65 to 94 to 89	0.4	0.66	36 mm rain during previous week with 18.5 mm on June 11 with 0.4 mm runoff. Photos show moist to wet manure with ponded water in few low spots, slurry not evident.
23-Jun-06	70	85 to 96	23.6	0.66	Previous week very wet with daily rain sof 31, 1, 0.5, 26, and 7 mm. Runoff was 9 mm (31 mm rain), 13 mm (26 mm rain), and 2 mm (7 mm rain). Photos show very wet conditions, with lots of runoff in feedlots and ditches, with slurry.
18-Jul-06	10	96 to 59	0	0.04	Previous 3 weeks very dry with 10 mm rain. Photos show drying conditions with granular surface to wet puddles with deep manure pack
9-Aug-06	0	60	0	0.06	Very little rain for previous 3 weeks (25 mm with 10 on July 4, 6 on Aug 4, 4 on Aug 5). Photos show dry granular surface.

P: rainfall, ROp: predicted runoff, VMCp: predicted volumetric moisture content.

Model Sensitivity Analysis

Model output, daily runoff amount is evaluated as to its sensitivity to changes in input parameters. The output parameters of a properly designed model will react within a range consistent with that expected of real systems as the input parameters are varied. The amount of runoff is affected by the amount of rainfall, stocking density, and drying conditions (potential evaporation). The depth of liquid within a runoff storage pond will be dependent upon the amount of runoff received, the seepage rate through the pond bottom, and the pond surface area that receives direct rainfall and loses evaporation atht the same rate of potential evaporation. The effect of these input parameters is portrayed upon several days of rain in Sept 2006 from Saskatoon (Table 5.4) and upon summation parameters for 2006 rain season (April 1 to October 31) (Table 5.5). Decreasing the stocking density such that there are no cattle in the pen (Pc = 0 mm/d) makes for a slightly drier manure pack (S for a Pc of 0.75 mm/d is 31.4 on Sept 14 whereas for a Pc of 0 mm/d S is 29.6) and this results in a lower runoff volume from the Sept 15th rains (30.9 mm to 27.7 mm) and in a storage pond depth 0.33 m lower. A pond with a low hydraulic conductivity and thus low seepage rates (0.1 mm/d) will have deeper storage in the pond (1.99 m on Sept 15th as opposed to 1.90 m with a seepage rate of 1 mm/d).

Table 5.4. Effect of varying stocking density on cattle contributions of water (Pc) and storage pond seepage rate (D) upon runoff parameters upon Saskatoon data.

Date	P	Pc	D	dPE	S	CNp	ROp	Hs
	mm	mm	mm/d	mm/d	mm		mm	m
12-Sep-06	0	0.75	0.1	0	1.0	57	0.0	0.82
13-Sep-06	24				24.2	88	0.0	0.84
14-Sep-06	7.5				31.4	94	0.0	0.84
15-Sep-06	46				37.5	96	30.9	1.99
14-Sep-06	7.5	0	0.1	0	29.6	92	0.0	0.54
15-Sep-06	46	"	"		37.5	96	27.7	1.66
14-Sep-06	7.5	0.75	0.1	1	29.1	92	0.0	0.42
15-Sep-06	46	"	"		37.5	96	27.6	1.55
14-Sep-06	7.5	1.5	0.1	0	33.7	95	0.2	1.33
15-Sep-06	46	"	"		37.5	96	35.0	2.47
14-Sep-06	7.5	0.75	1.0	0	31.4	94	0.0	0.73
15-Sep-06	46	"	"		37.5	96	30.9	1.90

P: daily rainfall amount, Pc: daily water contribution from cattle which is affected by stocking density. dPE: change in potential evaporation with positive values meaning an increase. D: seepage rate through bottom of storage pond. S: amount of water in 50 mm of manure pack 37.5 is maximum. CNp: Curve number of drying model. Hs: depth of liquid in storage pond with 3:1 sides.

Some of the seasonal parameters show greater effects (Table 5.5). Decreasing the cattle input parameter to 0 mm/d decreases manure moisture content and CN values slightly and total runoff from 74 to 57 mm and maximum pond depth by 0.43 m. Increasing stocking density such that cattle input is doubled, 1.5 mm/d, increases total runoff to 108 mm and maximum pond depth by almost 1 m. Increasing potential evaporation rate by 1 mm/d (26% seasonal increase) has a similar effect upon runoff, decreasing total runoff and maximum storage depth by about 20%. The potential evaporation effect is reduced upon drying of the manure pack due to the AE/PE ratio that is used for dry manure packs, however the storage pond removal is calculated using PE.

Table 5.5. Effect of varying model input parameters upon summation output parameters for April 1 to October 31, 2006 using daily Saskatoon climate values

Input Parameters			Output Parameters						
Pc	D	dPE	tPCs	tPE	avSM	avCN	tROs	avDs	maxHs
mm/d	mm/d	mm/d	mm	mm	mm	n	mm	m	m
0.75	0.1	0	562	799	17	77	74	1.00	2.48
0	0.1	0	401	799	14	74	57	0.77	2.05
1.50	0.1	0	722	799	20	80	108	1.36	3.04
0.75	1.0	0	562	799	17	77	74	0.94	2.37
0.75	0.1	1	562	1013	13	73	59	0.70	2.00

Pc: water excreted by cattle. D: seepage rate through storage pond bottom. dPE: change in daily potential evaporation rate, positive values represent an increase. tPCs: seasonal precipitation and cattle input for April 1 to Oct 31. tPE: seasonal potential evaporation. avSM: average daily manure pack moisture for the season. avCN: average daily CN value for the season. tROs: seasonal runoff. avHs: average daily storage pond depth for the season. maxHs: maximum pond depth for the season.

6. Saskatchewan Climate and Feedlot Runoff

6.1 Saskatchewan Climate

Saskatchewan is described as having a cool sub-humid to semi-arid climate, due to the cold winters and the high potential evaporation relative to precipitation. Our study only considers the period April 1 to October 31 when rains occur. The southwest corner of Saskatchewan is dry with average rainfalls between 240 and 300 mm (Fig. 6.1a) and with high potential evaporations (PE) of 800 to 850 mm (Fig. 6.1b). The northern and eastern part of the agricultural region is wetter with average rain falls of 300 to 400 mm and PE values of 700 to 800 mm. Of concern for runoff is that of high daily rainfall events or wet seasons which can be represented by one in 25 year occurrences (Fig. 6.1 c and d). One in 25 year 24 hr rainfalls are 60 to 80 mm. Seasonal (April 1 to Oct. 31) rainfall amounts are greater than 1-in-25 year 24 hr rains (Fig. 6.1 c). One-in-50 year seasonal occurrences are about 10% higher than 1-in-25 year seasonal values. The Northeast and southeast regions of Saskatchewan have the greatest potential for large runoff amounts and accumulations due to higher rainfall and lower potential evaporation.

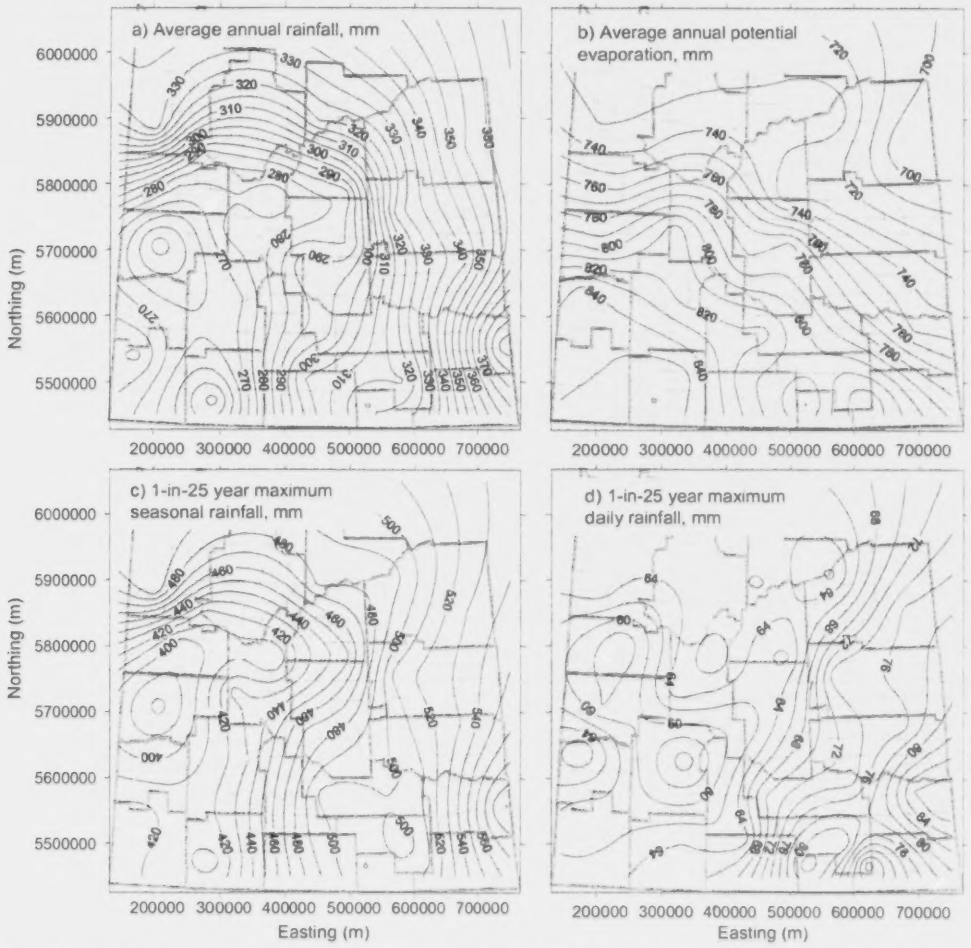


Fig. 6.1 Rainfall and potential evaporation characteristics for agricultural region of Saskatchewan.

6.2 Feedlot Runoff

Application of the runoff model to the 27 climate stations produced maps of runoff amount (mm of runoff). Shown here are two maps; the maximum 24 hour 1-in-25 year runoff (Fig. 6.2) and maximum seasonal 1-in-25 year runoff (Fig. 6.4). Maps of frequencies: average, 1-in-10, 1-in-50, and 1-in-100 are located in appendix C. The lowest 24 hour 1-in-25 year runoff values, 30 mm, occur in western Saskatchewan, whereas the highest values, 50 mm occur in eastern Saskatchewan (Fig. 6.2). The combination of higher 1-in-25 year precipitation amounts and higher antecedent moistures (lower PE) produce a greater difference in runoff amounts between the east and west parts of Saskatchewan. During the 66 years of data only 7 out of the 27 locations produced runoffs of greater than 75 mm in one day. For six locations this only occurred once in the 66 years, however for one location, Whitewood, this occurred 3 times. The average greatest daily runoff amount during 66 years from the 27 stations was 59 mm with a standard deviation of 21 mm. The greatest runoff, 127 mm, occurred in Ceylon (July 10, 1946 from a rainfall of 169 mm). The USDA (Safely et al., 1996) uses 24 hr, 1-in-25 year rainfall amounts to determine earthen feedlot runoff with a CN value of 90. Using this CN value of 90, a 60 mm 24 hour storm in western Saskatchewan produces 37 mm of runoff (overestimating runoff compared to our model, Fig. 6.2), whereas an 80 mm storm in eastern Saskatchewan produces 54 mm of runoff (about equivalent to our model, Fig. 6.2). One-in-50 year runoff amounts from 24 hr rains are 1.17 to 1.19 times larger than 1-in-25 year values of Fig. 6.2.

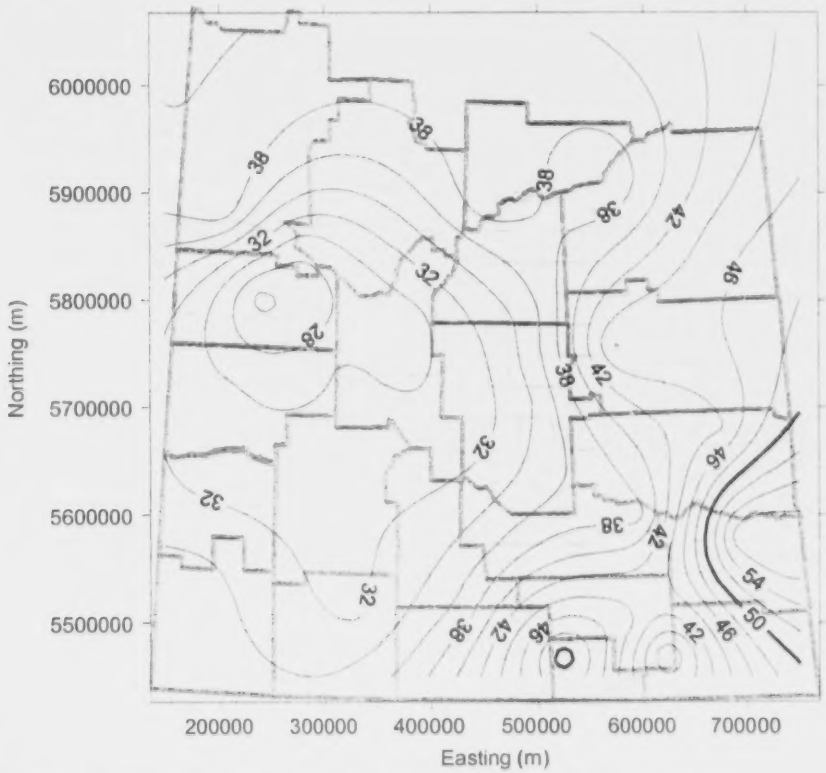


Fig. 6.2. Maximum 24 hour, 1-in-25 year runoff (mm) from cattle feedlots.

Seasonal 1-in-25 year runoff amounts range from 60 mm (west) to more than 120 mm (east) with 89 mm being the average for the 27 stations (Fig. 6.3). These 1-in-25 year seasonal runoff amounts are about 3 times that of annual averages and about 1.18 times less than 1-in-50 year amounts. Generally stations in the central to western parts of the agricultural region had no occurrences of 75 mm or greater (Harrison, Kindersley, Leader, Maple Creek, North Battleford) to one occurrence (Scott, Valmarie, Saskatoon) of seasonal runoff in 66 years greater than 75 mm. The east part of Saskatchewan had 5 to 10 occurrences per station within 66 years (Hudson Bay, Indian Head, Moosomin, Whitewood). Saskatchewan regulations use runoff planning accommodation of 75 mm of runoff (Farm facts 1999) from daily events.

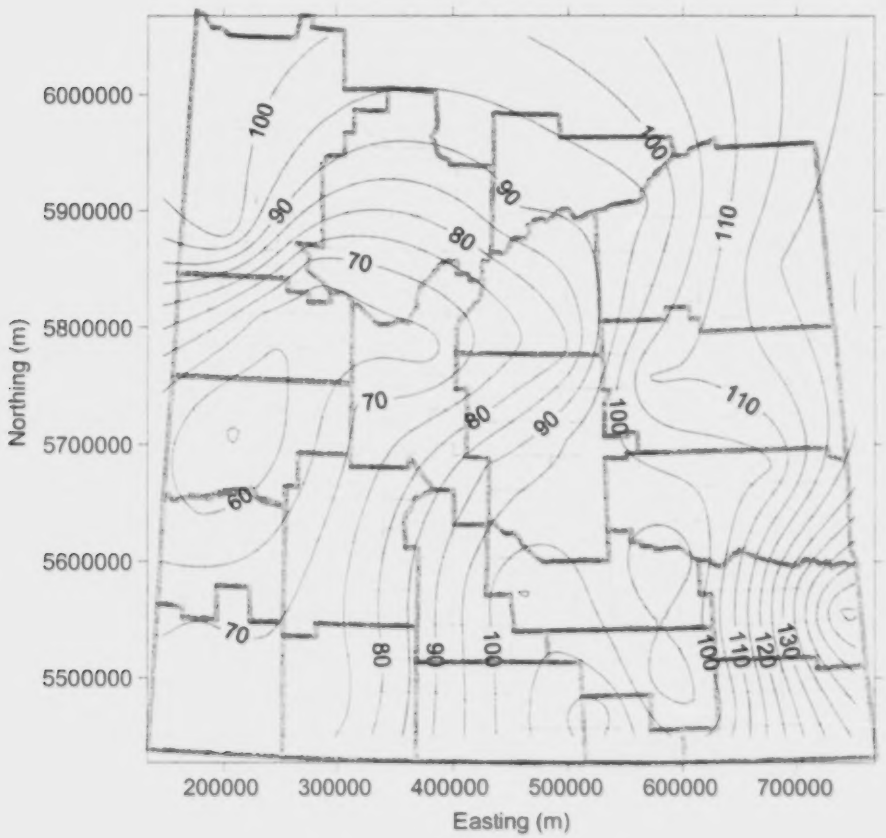


Fig. 6.3. Seasonal (April 1 to Oct 31) 1-in-25 year daily runoff (mm) from cattle feedlots.

6.3 Feedlot Storage Pond

Earthen manure storage systems should be designed to hold 400 days of storage (SAFRR 2003) or to accommodate 75 mm of runoff from a daily rain event (SAF, 1999). We utilized a storage pond with 3:1 slopes, with bottom sides of 25 m x 25 m that would accommodate runoff from 4 ha of pens. For this type of pond, 75 mm of runoff would be about 2.7 m deep, 90 mm would be 3 m, 100 mm 3.2 m, and 150 mm close to 4 m depth. At a depth of 3.0 m the storage pond would have an area of about 2000 m^2. This relationship between area, depth, and volume will change dependent upon the initial size of the bottom and upon slopes.

The feedlot model had a storage pond component that incorporated these pond and allowed for seepage from the bottom (hydraulic conductivity of approximately 1 x 10^{-7} cm/s with unit gradient and rounded to 0.1 mm/d), for evaporation from the pond surface to occur at potential evaporation rates, and for rainfall to directly contribute to the pond surface. The map for the maximum seasonal pond depth that occurred with a 1-in-25 year period is shown in Fig. 6.4. Generally the west part of Saskatchewan has 1-in-25 year depths of 2.2 to 3 m, while the east half is 3.2 to 4 m. These depths are about 2.5 to 2.9 times the average annual maximum depths (ranged from 0.75 to 1.32 m). One-in-50 year maximum pond depths were about 1.18 times that of the 1-in-25 year depths.

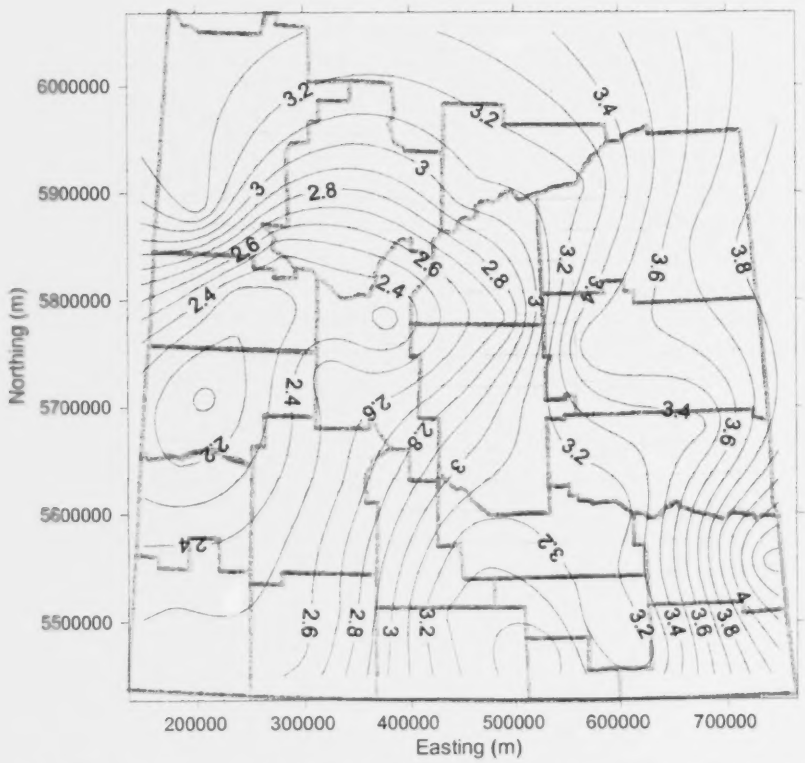


Fig. 6.4. Maximum seasonal (April 1 to Oct 31) storage pond depth (m) for 1-in-25 year accumulation of runoff (mm) from cattle feedlots. Depth of 2.7 m is equivalent to 75 mm of runoff; 3.0 m is equivalent to 90 mm, 3.2 m is 100 mm, and 4.0 m is 150 mm of runoff.

Kindersley, the driest region, had less than 0.10 m of liquid remaining in the storage pond on October 31, in 41% of the years (27 of 66). Davidson, in the center of this region with a 1-in-25 year seasonal pond depth of 2.86 m had 15 years (23%) in which the pond depth on October 31st was less than 0.1 m. The use of evaporation and lower runoff amounts can be used to effectively create evaporative ponds that do not require frequent emptying. Going to larger pond design could increase the number of years that evaporation could be used as the main means for emptying ponds.

If pond sizing and pond emptying frequency is to be determined by the 1-in-25 year pond depth, then a storage pond and feedlot size as described by the model will be sufficient to seasonal account for 3 m of runoff storage (90 mm of runoff after accounting for evaporation, direct rainfall, and seepage) for the western half, whereas storage ponds in the eastern half will have to account for 4 m of runoff storage (150 mm of runoff after accounting for evaporation, direct rainfall and seepage).

7.0 Summary, Conclusions, and Recommendations

7.1 Summary and Conclusions

The goal of this study was to construct and validate a runoff model that incorporates regional climate and soils conditions that will aid feedlot design. Thus the primary objective was to develop a regional runoff model so that feedlot runoff within the agricultural region of Saskatchewan can be represented. To accomplish this main goal three secondary objectives had to also be investigated:

i. To determine the amount of moisture that can be stored and retained within the manure pack and surficial soil layer;
ii. To determine the amount of moisture that can drain (move downwards) from the manure pack and the surficial soil layer; and
iii. To determine the amount of moisture removed from the manure pack and surficial soil layer in response to evaporation.

i. Manure pack moisture content

The feedlot manure pack is critical to retaining water and preventing it from running off. A bare compacted feedlot surface has a very high runoff potential. A manure pack can detain moisture by absorption and surface detention. The moisture content of the feedlot manure pack can range from 0.02 to 0.70 kg/kg (wb) and rapidly absorbs water when dry. At moisture contents above 0.68 kg/kg the manure pack is a slurry if disturbed by cattle and will flow under its own weight. At these moisture contents the surface is smooth and will not detain any runoff waters. At moisture contents of 0.52 to 0.68 kg/kg (wb) the manure pack is plastic, tending to retain shape if disturbed. At these moisture contents the surface is very rough, as disturbed by cattle, and there is too much moisture for compaction. Moisture contents of 0.32 to 0.52 kg/kg (wb) the manure pack is moist and friable, clods can easily break up and the pack can become compacted by cattle. At moisture contents less than 0.32 kg/kg the manure pack starts to become dry to touch and brittle. Action by cattle results in a granular layer of manure on top of a compacted brittle impervious layer.

Undisturbed manure packs (bulk density of 477 kg/m^3) holds 0.59 kg/kg (wb or 0.69 m^3/m^3 volumetric moisture) at saturation and drains to 0.51 kg/kg (0.61 m^3/m^3) after 3 hours. The manure pack dry bulk density is within the range of 400 to 480 kg/m^3 unless appreciable soil is mixed within it (bulk density increases to 500 kg/m^3 and more), is composed largely of straw (bulk density decreases to 200 kg/m^3 or less) or is liquid (slurries can be 370 kg/m^3 in dry bulk density).

ii. Downward drainage

Moisture draining through the manure pack and into the soil surface can remove excess water from the manure pack and from runoff. Manure packs with little soil and not compacted can have saturated hydraulic conductivities of 2.8 x 10^{-3} cm/s (100 mm/hr) and greater. Lab measured infiltration rates ranged from 480 to 1500 mm/hr with manure at a bulk density of 477 kg/m^3. Within an active feedlot pen excess rain water would

rapidly drain to the bottom of a manure pack, however would soon become mixed in by cattle, thus creating slurry conditions.

Undisturbed soil cores of compacted manure and the manure soil interface had geometric saturated hydraulic conductivities of 3 to 5 x 10^{-6} cm/s (0.1 to 0.2 mm/hr). This is within the range or greater than field studies (Kennedy et al., 1999; Maule and Fonstad, 2002) or another lab core study (McCullough et al., 2001), but much less than a study using tension infiltrometer which did not allow the floor to saturate (Miller et al., 2004). Due to these low rates that the majority of studies found in active feedlots we thus assumed that downward drainage was 0 mm/d and would have no impact upon water loss during a runoff event or upon decreasing the moisture content in a wet manure pack during very wet conditions that might prevail during a one to two week period.

iii. Evaporation of water from manure pack

A lab study of water evaporation from manure provided the following relationship of evaporation and manure pack moisture content:

$$AE = PE\ (1.42\ VMC - 0.02)$$

where AE is actual evaporation rate (mm/d), PE is potential evaporation rate (mm/d as determined from climate parameters), and VMC is volumetric moisture content of the manure pack. This equation is effective for VMC values between 0.02 and 0.69 m^3/m^3 for active feedlots in which the manure pack is disturbed (mixed). At values of 0.69 m^3/m^3 and above AE=PE.

When this equation is incorporated with climatic measurements of daily rainfall and PE, with a manure pack depth of 50 mm, and allowing for contribution of moisture by cattle (0.75 mm/d for this study) it provided a general representation of measured manure pack moisture contents; measured vs predicted moisture contents had slopes of 0.99 for data that developed the model and 0.88 for data that was used to validate the model. This manure pack water balance was used within the runoff model.

Main Objective: Feedlot runoff

A feedlot runoff model was developed using the manure pack water balance model from the previous section and the Curve Number Method (CN). This model was developed using field data measured from a Lethbridge feedlot (Miller et al., 2003, 2004). With the exception of one out of 11 runoff events, our predicted CN model provided a slope of 0.99 ($r^2 = 0.84$) against their measured CN values. It was not possible to validate our model against other measured data sets as we did not succeed in obtaining working runoff weirs, however predicted runoff amounts, in general agreed, with observed (but not measured) runoff events.

Twenty-seven climate stations, with daily data from April 1 to October 31 for the years 1940 to 2006, were used to input rainfall and potential evaporation data into the runoff model. The 66 years of climate and runoff output data were used to develop maps showing 1-in-25 year 24 hr and seasonal maximum rainfall and runoff amounts. A model component calculated storage pond depth allowing runoff, rainfall, seepage, and evaporation into and from the pond. Only in the southeast (SE) region of the province

did the 24 hour maximum rainfall with a 25 year return period exceed 75 mm (Table 7.1). The driest portions of the province (SW and CW) had 24 hour maximum 1-in-25 year rainfalls of 62 mm. Maximum 24 hour 1-in-25 year runoff amounts ranged from 29 mm (CW) to 46 mm (SE). Of importance towards feedlot storage, pond design should be that of seasonal runoff amounts; maximum 1-in-25 year runoff amounts ranged from 62 mm in the CW to 112 mm in the SE and 1-in-25 year maximum pond depths ranged from 2.3 to 3.5 m for the same regions (Table 7.1).

Table 7.1. Climatic and feedlot runoff summary for Saskatchewan Agricultural Regions

Region	Crop District	average seasonal rain mm	1-in-25 yr max. seasonal rain mm	1-in-25 yr max. 24 hour rain mm	1-in-25 yr max. seasonal runoff mm	1-in-25 yr max. 24 hr runoff mm	1-in-25 yr max. storage depth m
SE	1,2, 3ASE, 5A	334	523	78	112	46	3.48
SW	3 ASW, 3AN, 3BN, 3BS, 4	267	418	62	72	33	2.51
CE	5, 6A	312	497	69	100	39	3.22
CW	6B, 7	269	400	62	62	29	2.28
NE	8, 9AE	323	487	66	97	39	3.21
NW	9AW, 9B	309	458	63	85	34	2.90

Regions and Crop District refer to agricultural portions within the province by Saskatchewan Agriculture and Food (http://www.agr.gov.sk.ca/). Refer to Fig. 3.10. **'Seasonal'** includes all rain or runoff from April 1 to Oct 31. **Storage depth** is depth of accumulated runoff in storage pond such that 75 mm of runoff would be 2.7 m deep, 90 mm 3 m, 100 mm 3.2 m deep.

Current Saskatchewan regulations ask that feedlot storage ponds be able to accommodate 75 mm of runoff from a daily rainfall. Such an amount would only occur for frequencies much in excess of a 1-in-100 year rain event. A 1-in-25 year 24 hour rain event for the agricultural region of the province is 68 mm, whereas a 1-in-25 year 24 hour runoff event averages 37 mm. It would be more appropriate to design storage ponds upon expected accumulation of seasonal runoff and rainfall minus seepage and evaporation losses in the runoff storage pond. Seasonal 1-in-25 year maximum rainfall amounts is 470 mm. Seasonal 1-in-25 year maximum runoff is 90 mm, and seasonal maximum storage pond depth is 3.0 m. These seasonal amounts will range by 50% between the dry and wet regions of the province (Table 7.1) and thus regional differences should be accommodated.

7.2 Recommendations

The following recommendations are for aid in sizing of feedlot storage ponds within the agricultural region of the province:

5. Storage ponds that are to be emptied only once, at the end of the rain season, should be designed upon seasonal (April 1 to October 31) 1-in-25 year maximum runoff. For dry regions of the province this will be 62 mm, however for wet regions of the province this will be 112 mm. These amounts do not include snowmelt runoff.
6. Sizing ponds based upon a daily runoff event of 75 mm is far too great for any 24 hr, 1-in-25 year runoff event and is even greater for than any 24 hr, 1-in-100 year runoff event, however is appropriate for some seasonal 1-in-25 year runoff amounts.
7. Within the dry regions of the province (SW and CW), storage ponds designed to hold 3 m depth, resulting from 75 mm of runoff will be dry at least 25% of the time. These regions could have storage ponds designed for evaporative control rather than emptying for irrigation.
8. Sizing ponds based upon maximum expected daily runoff does not allow for seasonal accumulation unless they are to be emptied several times a year.

The following recommendations address needs for further study:

1. Although feedlot floor infiltration rates are very low there is evidence of nutrients within groundwater underlying feedlots and the likelihood of by pass transport or higher seepage from inactive pens needs to be addressed;
2. The contribution of snow accumulation within pens during winters and contribution of snowmelt waters to storage pens needs to be addressed. Some of this can be done with a runoff model and long term climate information; however some of this needs field observations and measurements. Within the literature there is a lack of any such information (one study done in South Dakota in the early 1970s).
3. The rainfall and runoff maps produced here should be extended into southern Manitoba and Alberta. This can be easily done using the existing model and readily available climatic data.
4. There is a need to assess whether intense storms are becoming more frequent or/and more intense in the last 10-20 years then long term average.
5. The runoff model produced here, although appears to work well, still requires validation against a set of measured feedlot runoff data.
6. Further development of the runoff model can be done by adding a runoff chemistry component.

References

Powers, W.J. and H.H. Van Horne. 2001. Nutritional implications for manure nutrient management planning. Applied Engineering in Agriculture. 17(1):27-39

ACFA and AAFRD (Alberta Cattle Feeders' Association) and AAFRD (Alberta Agriculture, Food and Rural Development. 2002. Beneficial Management Practices – Environmental Manual for Feedlot Producers in Alberta. http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/epw5837/$FILE/bmp_feedlot.pdf

ASAE 2003. Manure Production and Characteristics. ASAE D384.1 FEB03. American Society of Agricultural Engineers Standards.

ASCE. 2005. The ASCE Standardized Reference Evapotranspiration Equation. Edited by R. G. Allen, I.A. Walter, R. Elliott, T. Howell, D. Itenfisu, and M. Jensen. New York, NY: American Society of Civil Engineers.

Barth, C., T. Powers and J. Rickman. 1996. Chapter 4. Agricultural Waste Characteristics. In J. Krider (ed.) Agricultural Waste Management Field Handbook. National Engineering Handbook Part 651. Natural Resources Conservation Service. http://www.wcc.nrcs.usda.gov/awm/awmfh.html

Bergsrud, F.G. 1968. Annual totals and temporal distribution of cattle feedlot runoff in Kansas, Unpublished M.S. Thesis, Kansas State University, Manhattan, Kansas; cited in Larson et al., 1976.

Card, J. R. 1979. Synthesis of streamflow in a prairie environment. In The Hydrology of Areas of Low Precipitation: Proc. Canberra Symposium, 11–21. Dec. 1979. IAHS–AISH Publ. No. 128. Wallingford, Oxfordshire, U.K.: International Association of Hydrological Sciences.

Carter, Martin R. (editor) (1993). Soil Sampling and Methods of Analysis. Published by Lewis Publishers, Boca Raton, FL, USA. Pp. 14-17, 19-23, 530-532, 541-543, 574-578.

Clark, R.N., A.D. Schneider and B.A. Stewart. 1975. Analysis of runoff from Great Plains feedlots. Trans ASAE 18:319-322.

Coote, D.R. and F.R. Hore. 1977. Runoff from feedlots and manure storages in southern Ontario. CJAE 19:116-121.

Environment Canada. 2007a. Canadian climate normals or averages 1971-2000. http://www.climate.weatheroffice.ec.gc.ca/climate_normals/index_e.html. Accessed various times 2006-2007.

Environment Canada. 2007b. National climate data and information archive. http://www.climate.weatheroffice.ec.gc.ca/Welcome_e.html. Accessed various times 2006-2007.

Fields, W.J. 1971. Hydrologic and water quality characteristics of beef feedlot runoff. Unpublished M.S. Thesis, Kansas State University, Manhattan, Kansas. cited in Larson et al., 1976.

Gilbertson, C.B., T.M. McCalla, J.R. Ellis, O.E. Cross, W.R. Woods. 1971. Characteristics of runoff, solids, wastes, and nitrate movement on unpaved beef feedlots as affected by animal density and feedlot slope. Jour. Water Pollution Control Fed. 43:483-493.

Gilbertson, C.B., J.A. Nienaber, T.M. McCalla, J.R. Ellis, and W.R. Woods. 1972. Beef cattle feedlot runoff, solids transport and settling characteristics. TASAE 15:1132-1134.

Gray, D.M. (ed). 1970. Handbook on the Principles of Hydrology. Published by the Secretariat, Canadian National Committee for the International Hydrological Decade, Water Information Center, Inc., 6800 Jericho Tpke., Syosset, NY, USA., pp. 8.90-8.96.

Gray, D. M., Landine, P. G., and Granger, R. J. 1985. Simulating infiltration into frozen prairie soils in stream¯flow models. Can. J. Earth Sci., 22, 464-474.

Hauser, V.L. 1975. Design runoff volumes from feedlots in southwestern Great Plains. In Managing Livestock wastes (Proceedings, International Symposium). ASAE Proc-75 pp. 426-428.

Jury, W., W.R. Gardner, and W.H. Gardner. 1991. Soil Physics. Published by John Wiley and Sons, Inc., New York, USA., pp. 29-30, 45, 47:80-83.

Kennedy, B., R. N. Coleman, G. M. Gillund, B. Kotelko, M. Kotelko, N. MacAlpine, and P. Penney. 1999. Feedlot Runoff: Volume 1: Quantity and quality of rainfall and snowmelt runoff from pens. CAESA Research Project RES-109-94.

Kizil, U. 2003. Development of a software program for feedlot hydrology/nutrient management and GIS database for North Dakota. Ph.D. Dissertation North Dakota State University, Department of Agricultural and Biosystems Engineering, Fargo, North Dakota.

Laguë, C., H. Landry, and M. Roberge. 2005. Engineering of land application systems for livestock manure: A review. Canadian Biosystems Engineering 47:6.17-6.28.

Larson, C.L., L.G. James, P.R. Goodrich, and J. Bosch. 1976. Performance of Feedlot Runoff Control Systems in Northern Climates. Transactions of ASAE: 1175-1180.

Madden, J.M. and J.N. Dornbush. 1971. Measurement of runoff and runoff carried waste from commercial feedlots. Pages 44-47 in International symposium on livestock wastes. Columbus, Ohio, US. April 19-22, 1971.

Manges, H.L., L.A. Schmid, and L.S. Murphy. 1971. Land disposal of cattle feedlot wastes. Pages 62-65 in International symposium on livestock wastes. Columbus, Ohio, US. April 19-22, 1971.

Maule, C, W. Helgason, S. McGinn, and H. Cutworth. 2006. Estimation of standardized reference evapotranspiration on the Canadian Prairies using simple models with limited weather data. Canadian Biosystems Engineering 48:1.1-1.11 http://www.engr.usask.ca/societies/csae/journal.html

Maule, C.P. and T.A. Fonstad. 2002. SoOlute and moisture flux beneath cattle feedlot pens. Transactions of the ASAE, 45(1):73-81.

McCullough, M.C., D.B. Parker, C.A. Robinson, and B.W. Auvermann. 2001. Hydraulic conductivity, bulk density, moisture content, and electrical conductivity of a new sandy loam feedlot surface. Applied Engineering in Agriculture 17(4): 539-544.

Meilke, L.N. and A.P. Mazurak. 1976. Infiltration of water on a cattle feedlot. Transactions ASAE 19:341-344.

Mielke, L.N., N.P. Swanson and T.M. McCalla. 1974. Soil profile conditions of cattle feedlots. Journal of Environmental Quality 3:14-17.

Miller, J, T. Curtis, B. Beasley, T. Ormann, F. Larney, T. McAllister,and B. Olsond. 2004a. Influence of soil texture on potential leaching from feedlots. Final Report to Alberta Beef Producers: Project No. 2001ACC003.

Miller, J.J, B.P. Handerek, B.W. Beasley, E.C.S. Olson, L. J. Yanke, F.J. Larney, T.A. McAllister, B.M. Olson, L. B. Selinger, D. S. Chanasyk, and P. Hasselback. 2004b. Quantity and quality of runoff from a beef cattle feedlot in southern Alberta. Journal Environmental Quality 33:1088-1097.

Miller, J.J., B. Handerek, E.C.S. Olsen, F.J. Larney, T.A. McAllister, L.J. Yanke, D.S. Chanasyk, B.M. Olson, L.B. Selinger, and P. Hasselback. 2003. Chapter 4. Quantity and quality of runoff from a beef feedlot in southern ALberta. In Managing feedlot manure to protect water quality and human health. Final Report. CABIDF, Project #97AB061. J.J. Miller (ed.).

Miner, J.R., L.R. Fina, J.W. Funk, R.I. Lipper and G.R. Larson. 1966. Stormwater runoff from cattle feedlots. Pages 23-27 in Management of farm animal wastes. Proceedings national symposium on animal waste management. ASAE publication No. SP-0366. Michigan State University, East Lansing, Michigan, US May 5-7, 1966. pp 23-27

Nicholaichuk, W. 1967. Comparative watershed studies in southern Saskatchewan. Trans. ASAE 10(4): 502–504.

Nienaber, J. A., C. B. Gilbertson, T. J. Klopfenstein, S. D. Farlin and T. M. McCalla. 1974. Animal Performance and Lot Surface Conditions as Affected by Feedlot Slope and Animal Densities. Proceedings from International Livestock Environment Sym posium, Lincoln, Nebraska. pp. 130-137.

Nolan, S.C., L.J.P. van Vliet, T.W. Goddard, and T.K. Flesch. 1997. Estimating soil loss from rainstorms. Canadian Journal of Soil Science 77(4):669-676.

NRCS (Natural Resources Conservation Service. 2001. Part 630 Hydrology. http://www.wcc.nrcs.usda.gov/hydro/hydro-techref-neh-630.html. Accessed 2006-07.

Olson, E.C.S., J.J. Miller, D.S. Chanasyk, B.M. Olson, F.J Larney, T.A. McAllister, L.J. Yanke, L.B. Selinger, and P. Hasselback. 2003. Chapter 2. Effects of Bedding Type and Within-Pen Location on Feedlot Runoff and Infiltration. In Managing feedlot manure to protect water quality and human health. Final Report. CABIDF, Project #97AB061. J.J. Miller (ed.).

Overcash, M.R. and R.L. Phillips. 1978. Dairy Feedlot Hydrology. Transactions of the ASAE:1193-1198, 1208.

Phillips, R.L. 1981. Maps of Runoff Volumes from Feedlots in the United States. 4th International Proceedings ASAE. pp 274-277.

Powers, W.J. and H.H. Van Horne. 2001. Nutritional implications for manure nutrient management planning. Applied Engineering in Agriculture. 17(1):27-39

SAF (Saskatchewan Agriculture and Food). 1999. Farmfacts: Holding Pond Site Selection and Design. 3M ISSN 0840-9447 LOHP0199. Government of Saskatchewan.http://www.agr.gov.sk.ca/docs/production/holdpondff.pdf

SAF (Saskatchewan Agriculture and Food). 2004. Beef Cattle Housing and Feedlot Facilities. Government of Saskatchewan. http://www.agr.gov.sk.ca/docs/production/housing_feedlot_facilities.asp. Accessed Jan 2007.

Safley, L.M., C. Dupoldt, F. Geter, D. Stettler, and T. Murphy. 1996. Chapter 10. Agricultural Waste Management System Component Design. In J. Krider (ed.) Agricultural Waste Management Field Handbook. National Engineering Handbook Part 651. Natural Resoruces Conservation Service. http://www.wcc.nrcs.usda.gov/awm/awmfh.html

SAFRR (Saskatchewan Agriculture, Food and Rural Revitilization. 2003. Environmental Review: Guidelines for Intensive Livestock Operations. 1M ISBN 0-88656-702-5. http://www.agr.gov.sk.ca/docs/programs_services/ILOreview2002.pdf. Accessed Jan 2007.

SCS (Soil Conservation Service). 1972. Section 4: Hydrology In National Engineering Handbook. SCS, referred to in SWAT 2005.

Southcott, P.H. and S.C. Lott. 1997. Preliminary results on soil permeability and physical characteristics of feedlot pens. Preliminary results on soil permeability and physical characteristics of feedlot pens. Proc. Of the 7th Aust. And NZ Conf. on Geomechanics, Adelaide. 6 pp.

Swanson, N.P., L.N. Mielke, J.C. Lorimner, T.M. McCalla and J.R. Ellis. 1971. Transport of pollutants from sloping cattle feedlots as affected by rainfall intensity, duration and recurrence. Pages 51-55 in International symposium on livestock wastes. Columbus, Ohio, US. April 19-22, 1971.

SWAT (Soil and Water Assessment Tool). 2005. Equations: Surface Runoff, Section 2 Chapter 1. SWAT Theoretical Documentation, Version 2005. http://www.brc.tamus.edu/swat/doc.html

Swenson, D.A. 1975. Feedlot runoff control systems. M.Sc. Thesis. Fargo, North Dakota State University, Ag. Eng Dept., cited in Kizil 2003.

Tossell, R.W., G.J. Wall, R.P. Rudra, W.T. Dickinson, and P.H. Groenevelt. 1990. The Guelph rainfall simulator II: part 2 – a comparison of natural and simulated rainfall characteristics. Canadian Agricultural Engineering. 32: 215-223.

Tossell, R.W., W.T. Dickinson, R.P. Rudra, and G.J. Wall. 1987. A portable rainfall simulator. Can. Agric. Eng. 29, 155-162.

USDA. 1996. Appendix 10C – Runoff from feedlots and evaporation. 651.1070. In Agricultural Waste Management System Component Design. Part 651. Agricultural Waste Management Field Handbook. http://www.wcc.nrcs.usda.gov/awm/awmfh.html

USDA. 1999. Appendix 4 – Agricultural waste characteristics. In Agricultural Waste Management System Component Design. Part 651. Agricultural Waste Management Field Handbook. http://www.wcc.nrcs.usda.gov/awm/awmfh.html.

Vanderholm, D.H. 1975. Nutrient losses from livestock waste during storage, treatment, and handling. In F.R. Hore et al., eds., Managing Livestock Wastes, Proceedings of the 3rd International Symposium on Livestock Wastes, pp. 282–284. American Society of Agricultural Engineers, St. Joseph, MI.

Wensink, R.B. and J.R. Miner. 1975. A Model to Predict the Performance of Feedlot Runoff Control Facilities at Specific Oregon Locations. Transactions of the ASAE: 1141-1145, 1150.

White, Lisa. Feedlot Hydrology. M.Sc. Thesis, University of Saskatchewan, Dept of Agricultural and Bioresources Engineering. Feb. 2006. Electronic version available at http://library2.usask.ca/etd/ETD-search/search

APPENDICE TABLE OF CONTENTS

Appendix A. Project Papers and Presentations

Appendix B. Extended Bibliography

Appendix C. Additional Information

C1. Photos of Feedlot Manure Pack Conditions C-1

C2. Maps:

24 hr Rainfall Amounts for Various Return Periods C-6

Seasonal Rainfall Amounts for Various Return Periods C-8

24 hr Runoff Amounts for Various Return Periods C-11

Seasonal Runoff Amounts for Various Return Periods C-14

Appendix A. Papers and Presentations

Thesis

White, Lisa. Feedlot Hydrology. M.Sc. Thesis, University of Saskatchewan, Dept of Agricultural and Bioresources Engineering. Feb. 2006. Electronic version available at http://library2.usask.ca/etd/ETD-search/search

Publications

Maule, C, W. Helgason, S. McGinn, and H. Cutworth. 2006. Estimation of standardized reference evapotranspiration on the Canadian Prairies using simple models with limited weather data. Canadian Biosystems Engineering 48:1.1-1.11 http://www.engr.usask.ca/societies/csae/journal.html.

Proceedings

Maule,C. and D. Chi. 2006. Development of an Evaporative-Runoff Model for Cattle Feedlot Pens. ASABE. 2006 ASABE Annual International Meeting, Portland, Oregon July 9-12, 2006. Paper No 064066. 12 pp

Maule, C. 2005. Prairie Feedlot Hydrology, Growing the Livestock Industry, Saskatoon, Saskatchewan, Oct 25-26, (2 pages).

Maulé, C., W. Helgalson, S. McGinn, and H. Cutforth. 2005. Estimation of standardized reference evapotranspiration on the Canadian Prairies using simple models with limited weather data. Canadian Society for Bioengineering Annual Meeting. Winnipeg, MB. Inn at the Forks. June 26-29, 2005. Presentation and paper #05-054, 16 pp.

Maulé, C., L. White, and T. Fonstad. 2005. Application of the Green-Ampt and Curve Number Models to Runoff from cattle feedlot pens. Canadian Society for Bioengineering Annual Meeting. Winnipeg, MB. Inn at the Forks. June 26-29, 2005. Presentation and paper #05-050, 18 pp.

White, L., C. Maulé, and T. Fonstad. 2005. Water balance of a prairie cattle feedlot pen. 6 pp. Soils and Crops Workshop, University of Saskatchewan, Feb 17-18, 2005.

Tang, K., C. Maulé, and L. White. 2003. Time Domain Reflectometry Probe Fabrication and Installation., 2003 CSAE/ASAE Annual Intersectional Meeting, Quality Inn & Suites, Fargo, North Dakota, USA, October 3-4, 2003. Presentation #RRV03-0024, 6 pp.

Conferences/Workshops without proceedings

Henderson, J., T. de Rosario and C. Maulé. 2006. Physical and Hydrologic Properties of Feedlot Manure. CSBE/ASABE North Central Inter-Sectional Conference October 5-7, 2006, Parktown Hotel, Saskatoon. MBSK 06-300

Herzog, I., T.A. Fonstad, and C. Maulé. 2006. Overview of surface hydrological conditions of Saskatchewan cattle feedlots. CSBE/ASABE North Central Inter-Sectional Conference October 5-7, 2006, Parktown Hotel, Saskatoon. MBSK 06-304.

Maulé, C.P. 2005. How can prairie waters be protected from intensive livestock farming. Panel presentation and discussion in 'Water Issues Forum' hosted by Office of the Vice President Research, University of Saskatchewan. Feb 25, 2005.

Maule, C., White, L. and Fonstad, T. (2005). Water gains and losses from cattle feedlot pens, North Central ASABE/CSBE, Brookings, South Dakota, United states, Sept 30 to Oct 1, Paper No. SD05503. Abstract

Sander, M., Maule, C. and Fonstad, T. (2005). Hydraulic properties of a feedlot manure pack; a preliminary investigation, North Central ASABE/CSBE Conference, Brookings, South Dakota, United States, Sept 30 to Oct 1, Paper No. SD05502. Abstract

White, L., C. Maule, T. Fonstad. 2004. Hydraulic and Physical properties of a feedlot pen floor. ASAE/CSAE Annual International Meeting, Aug 1-4, 2004, Ottawa, Ontario. Abstract 042163 210-35. Abstract

Maule, C. and T. Fonstad. Feedlot Hydrology. 2004. SAFRR Workshop on Manure, Soil and Water Issues. June 15, 2004.

Rinas, D, T. Fonstad, and C. Maule. 2002. Hydrology of a Cattle Feedlot. ASAE/CSAE North Central Intersectional Conference. Sept 27-28. Saskatoon, SK Abstract

Reports

Herzog, Iain. 2006. Infiltration Manual

Herzog, Iain. 2006. Feedlot Survey

Abstracts

Rinas, D, T. Fonstad, and C. Maule. 2002. ***Hydrology of a Cattle Feedlot****. ASAE/CSAE North Central Intersectional Conference. Sept 27-28. Saskatoon, SK Abstract*

The objective of this project is to define the hydrology of prairie cattle feeding operations so that excess water leaving the feedlot via drainage and runoff can be better assessed as to contaminant potential. Site instrumentation was established during the summer of 2002 and monitoring of piezometers, precipitation, evaporation, infiltration and runoff, soil moisture, and solute concentrations will continue for a 5 year period. Results will assist rural municipalities and provincial regulators in siting these facilities. Additional benefits of the results will be an increased knowledge of the potential for movement of contaminated water into the soil or off these sites. The presentation will cover installation of the monitoring program and results from preliminary infiltration-runoff measurements.

White, L., C. Maule, T. Fonstad. 2004. ***Hydraulic and physical properties of a feedlot pen floor****. ASAE/CSAE Annual International Meeting, Aug 1-4, 2004, Ottawa, Ontario. Abstract 042163 210-35*

BENEFITS:

This study is concerned with providing better siting recommendations of earthen beef feedlots in the cold semi-arid climate of Saskatchewan. Although the annual precipitation is low there is concern about the amount of quality of runoff and potential groundwater recharge underlying beef feedlots. This study will eventually provide information as to the overall water balance of a feedlot including that of the manure pack, the feedlot pens, and the collection ponds.

PROPOSAL:

Earthen floor feedlot pens are common practice within the Canadian west. Of concern is that of the amount and quality of excess water (precipitation and waste) that runs off or drains down from the feedlots. The purpose of this study was to characterize the physical and hydraulic properties of the earthen feedlot floor controlling infiltration. Hydraulic characteristics were investigated of two beef feedlot pens; one 7 year old pen and one 1-year old pen in southwestern Saskatchewan. Infiltration was measured with a modified Guelph rainfall simulator and with double ring infiltrometers. Saturated hydraulic conductivities (falling head permeater), texture, bulk density, and moisture retention properties were measured from core and undisturbed blocks taken from soil and manure with in the top 45 cm of the feedlot surface. Results will be presented comparing the properties of surface manure crust, the manure pack, the manure soil interface, and that of deeper (35 to 45 cm) soils.

Maule, C., White, L. and Fonstad, T. (2005). ***Water gains and losses from cattle feedlot pens****. North Central ASABE/CSBE, Brookings, South Dakota, United states, Sept 30 to Oct 1, Paper No. SD05503. Abstract*

Excess water from cattle feedlots can be both of environmental concern and that of the comfort of the cattle, if not properly managed within feedlot design. Towards more efficient siting guidelines, feedlot design, and management, we determined the amounts of water that enter and leave the feedlot and their pathways. For this study we used measured (ours and that published) information to generate 'average' and 'extreme' conditions that have and might occur within Prairie feedlots. Water inputs are by precipitation (rain and snow) and by cattle excretion. Typical annual precipitation for the agricultural region of the prairies will range from 350 to 450 mm. Cattle contribution from pens at normal stocking densities will easily contribute as much as annual precipitation. Water losses are by evaporation, within the manure pack when the pens are cleaned, by runoff, and by drainage through the earthen floor of the pen. Evaporation of water from the feedlot pens is by far the greatest loss component (400-500 mm). The manure pack and bedding can retain large amounts of water (40 to 60 mm of water per 100 mm of pack) and thus when the pens are cleaned, between 100 and 200 mm of water are removed. Runoff amount and occurrence is the major environmental concern and can vary from 50 mm per year (one in 3 to 10 year occurrence) to 0 mm for dry years. Drainage is the smallest component, due to the compacted feedlot floor and is about 5 mm/yr. There is a possibility to utilize the dryness of the prairie climate to the benefit of feedlot

management. The manure pack and bedding can absorb great amounts of water and buffer the occurrence and amount of runoff and drainage. The high evaporation of our climate can create dry conditions that will enhance this and create a comfortable environment for the cattle. However, the unpredictability of rains can make this difficult to manage.

Sander, M., Maule, C. and Fonstad, T. (2005). ***Hydraulic properties of a feedlot manure pack; a preliminary investigation****. North Central ASABE/CSBE Conference, Brookings, South Dakota, United States, Sept 30 to Oct 1, Paper No. SD05502. Abstract*

Of primary environmental concern with open air cattle feedlots is that of water runoff. Feedlots are designed to accommodate a certain volume of runoff. Common design guidelines either use storm return periods (e.g. one in 25 year-24 hour storm) or specific runoff depths (e.g., 3 inches). The general purpose of our research program is to develop a predictive model that would forecast runoff amount from cattle feedlot pens, given specific storm size and antecedent moisture conditions. Of key importance in a runoff model is that of the manure pack itself. The key objectives of this presentation will be to address hydraulic properties of the manure pack that can affect runoff; hydraulic conductivity, saturated moisture content, retention of water against drainage, drying rates, and surface detention. Information from a laboratory study and a field study will be presented.

Herzog, I., T.A. Fonstad, and C. Maulé. 2006. ***Overview of surface hydrological conditions of Saskatchewan cattle feedlots****. CSBE/ASABE North Central Inter-Sectional Conference October 5-7, 2006, Parktown Hotel, Saskatoon. MBSK 06-304.*

Canadian prairie cattle feedlots are open-air earthen floored systems.

Feedlot design must be able to accommodate extreme precipitation rainfall events so that prolonged periods of in pen ponding are avoided and storage ponds can adequately store the runoff. The purpose of this study was to overview the ability of Saskatchewan cattle feedlot pens to handle excess water (runoff) from wet climatic conditions and to provide recommendations as to pen and feedlot management and design. About ten feedlots of differing size, age, construction, and management were visually assessed during a site visit during a wetter than normal period. Assessment considered pen size and slope, stocking density, manure management, bedding amount and placement, containment ponds, and drainage ditches. Additional site information, soils, geology, climate, were also factored into discussion.

Henderson, J., T. de Rosario and C. Maulé. 2006. ***Physical and Hydrologic Properties of Feedlot Manure****. CSBE/ASABE North Central Inter-Sectional Conference October 5-7, 2006, Parktown Hotel, Saskatoon. MBSK 06-300*

In conjunction with the improving the understanding and modelling accuracy of infiltration and runoff of rainfall from cattle feedlots, a variety of tests were done in the laboratory in order to better understand the physical properties of feedlot manure. These tests included retention against evaporation, water absorption, drainage against gravity, saturated hydraulic conductivity, manure particle size distribution, and testing for the plastic limit, liquid limit, and solid limit.

Two types of manure were tested; that collected after spring snow melt (manure had accumulated from fall pen cleaning until May) and that collected after much of the summer had passed (manure had accumulated from spring pen cleaning until August). The tests used were adapted from existing standards for soil testing. The presentation will provide an overview of the types of adaptations necessary for determining physical properties of manure; results of the tests with emphasis upon differences between the two types of manure; and relevance of these results in improving understanding of infiltration and runoff parameters of feedlots.

Appendix B. Extended Bibliography

Following section includes all literature found upon feedlots, whether or not used in the final report.

ACECSS (Agriculture Canada Expert Committee on Soil Survey. 1987 [new date]. The Canadian System of Soil Classification. Research Branch, Agriculture Canada. Second Edition 1987.

ACFA (Alberta Cattle Feeders' Association) and Alberta Agriculture, Food and Rural Development. 2002. *Beneficial Management Practices – Environmental Manual for Feedlot Producers in Alberta.* Web Site Alberta Agricutlure, Food and Rural Development. http://www1.agric.gov.ab.ca/$department/deptdocs/nsf/all/epw5837 (November, 2004).

AFIF. 2000. Effect of water quality upon cattle weight gain. (have pdf file 'AFIF 2000.pdf').

Agassi, M., I. Shainberg, and J. Morin. 1981. Effect of electrolyte concentration and soil sodicity on infiltration rate and crust formation. Soil Science Society of America Journal 45:848-851.

Agricultural Operation Practices Act, Province of Alberta, Revised Statutes of Alberta, 2000. Chapter A-7. Queen's Printer Bookstore, http://www.gov.ab.ca/qp.

Agri-news. 1999. Options for handling feedlot pen runoff. Agri-news Jan Feb 1999, Alberta Agr. (Agri-news 99.htm).

Allen, R.G., L.S. Pereira, D. Raes, and M. Smith. 1998. Crop evapotranspiration – Guidelines for computing crop water requirements. FAO Irrigation and drainage paper 56. Rome, 1998. http://www.fao.org/docrep/X0490E/x0490e00.htm#Contents

Alley, W. M. 1984. The Palmer Drought Severity Index: Limitations and assumptions. Journal of Climate and Applied Meteorology, 23, 1100{1109.

Anonymous, 1990. Manure Production and Characteristics. ASAE D384.1. ASAE Standards 1990. Pg 463-464.

Anonymous, 2000. Code of Practice for Responsible Livestock Development and Manure Management. Alberta Agriculture, Food and Rural Development.

Anschutz, J.A., J.K.Koelliker, J.J. Zovne, T.A. Bean, and M.J. Peterson. 1979. Sizing components of an open feedlot runoff-control systems. TASAE 22: 803-808. Anschutz et al., 1979 (applied Zovne et al 1977)

ASAE 2003. Manure Production and Characteristics. ASAE D384.1 FEB03. American Society of Agricultural Engineers Standards.

ASCE. 2005. The ASCE Standardized Reference Evapotranspiration Equation. Edited by R. G. Allen, I.A. Walter, R. Elliott, T. Howell, D. Itenfisu, and M. Jensen. New York, NY: American Society of Civil Engineers.

Barth, C., T. Powers and J. Rickman. 1996. Chapter 4. Agricultural Waste Characteristics. In J. Krider (ed.) Agricultural Waste Management Field Handbook. National Engineering Handbook Part 651. Natural Resources Conservation Service. http://www.wcc.nrcs.usda.gov/awm/awmfh.html

Bayne, G., 1996. Determination of Nutrient Values of Manure in Saskatchewan.

Bennett, M.R., and D.N. Graveland. 1976. A study of the impact of cattle feedlots on soils and shallow groudnwter. Technical Development Branch, Alberta Environment, Edmonton.

Bergsrud, F.G. 1968. Annual totals and temporal distribution of cattle feedlot runoff in Kansas, Unpublished M.S. Thesis, Kansas State University, Manhattan, Kansas; cited in Larson et al., 1976.

Bork, R and Marx. nd. Alberta feedlot management guide; facility design to protect the environment. Poster presentation. (Borg n Marx.pdf)

Brenton, P., and D. Mellish, 1996. The Development of an On-Farm Manure Management Program (electronic version). Nova Scotia Department of Agriculture.

Butchbaker, A.F. and M.C. Paine. 1975. Principles of feedlot runoff control. NebGuide G575-214, Coopoerative Extension Service, University of Nebraska, US, 4 pp

Butcher, J.E., L.E. Harris, and R.J. Raleigh. 1959. Water requirements for beef cattle. Utah Farm & Home Sci. 20:72-73.

C. M. Zehnder and A. DiCostanzo. 1997. Estimating feedlot nutrient budgets and managing manure output. 1997 Minnesota Cattle Feeder Report B-450.

Campbell, L.B. and G.J. Racz. 1975. Organic and inorganic P content, movement and mineralization of P in soil beneath a feedlot. Can. J. Soil Sci. 55:457-466.

Card, J. R. 1979. Synthesis of streamflow in a prairie environment. In The Hydrology of Areas of Low Precipitation: Proc. Canberra Symposium, 11–21. Dec. 1979. IAHS–AISH Publ. No. 128. Wallingford, Oxfordshire, U.K.: International Association of Hydrological Sciences.

Carter, Martin R. (editor) (1993). Soil Sampling and Methods of Analysis. Published by Lewis Publishers, Boca Raton, FL, USA. Pp. 14-17, 19-23, 530-532, 541-543, 574-578.

Chanasyk, D.S. and C.P. Woytowich. 1986. Snowmelt runoff from agricultural land in the Peace River Region. Can. Agric. Eng. 28:7-13.

Chen, Y.R. 1982. Engineering properties of beef cattle manure. Procceedings, Paper No. 82-4085. 1982 Summer meeting of ASAE, University of Wisconsin-Madison June 27-30, 1982.

Chu, S.T. 1997. Infiltration model for soil profiles with a water table. Trans. ASAE 40(4), 1041-1046.

Clark, R.N., A.D. Schneider and B.A. Stewart. 1975. Analysis of runoff from Great Plains feedlots. Trans ASAE 18:319-322.

Clark, R.N., C.B. Gilbertson and H.R. Duke. 1975. Quantity and quality of beef feedyard runoff in the Great Plains. Managing livestock wastes. Pages 429-431 in Proceedings of the 3rd international symposium on livestock wastes. ASAE, St. Joseph, Michigan, US.

Clyde, G. W. 1999. USEPA Postion Paper. Measurement of TSS in runoff. (Clyde TSS 1999.pdf).

Coleman, E. A., Walter Grub, R. C. Albin, G. F. Meenaghan and D. M. Wells, 1971. Cattle Feedlot Pollution Study. Interim Report No. 2 to Texas Water Quality Board. Texas Tech University Water Resources Center, Lubbock Texas.

Coleman, R.N., B. Kennedy, G.G. Gillund, N. MacAlpine, B. Kotelko, and P. Penney. 1996. Microbiological and chemical components of feedlot runoff. Paper No. 96-204 CSAE Annual Conference July 7-10 Lethbridge, Canada.

Coote, D.R. and F.R. Hore. 1977. Runoff from feedlots and manure storages in southern Ontario. CJAE 19:116-121.

Dantzman, C.L., M.R. Richter, and F.G. Martin. 1983. Chemical elements in soils under cattle pens. JEQ 12:164-168.

Davis, J. G., T. L. Stanton, and T. Haren, 1998. Feedlot Manure Management (electronic version). Colorado State University Cooperative Extension.

Davis, J.G. , T.L. Stanton, and T. Haren. 2002. Feedlot manure management no. 1.220. Published by Colorado State University Cooperative Extension. From website: http://www.ext.colostate.edu/pubs/livestk/01220.pdf

Department of Agriculture (Australia). 2002. Guidelines for Environmental Management of Beef Feedlots in Western Australia. Bulletin 4550. (Aust Ag 2002.pdf).

Dill, Gregg and Keith Boras, 1994–1995. Quality of Feedlot Manure for Irrigated Crop Production. Applied Research Report, 1994–1995. Irrigation and Resource Management Division, AAFRD.

Ellis, J.R., L.N. Mielke, and G.E. Schuman. 1975. The nitrogen status beneath beef cattle feedlots in eastern Nebraska. SSSAP 39:107-111.

Environment Canada. 2004a. Canadian Climate Normals 1971-2000, Eston, Environment Canada, http://www.msc-smc.ec.gc.ca/climate/climate_normals/index_e.cfm. (December, 2004)

Environment Canada. 2004b. Kindersley climatic data. http://www.msc-smc.ec.gc.ca/climate/ (December 2004)

Environment Canada. 2004c. Kindersley rainfall intensity-duration-frequency data. Obtained from Environment Canada, Meteorological Service of Canada, Prairie and Northern Service.

FarmFacts. 1999. Holding pond site selection and design. Saskatchewan Agriculture and Food. 3M ISSN 0840-9447 LOHP0199. http://www.agr.gov.sk.ca/docs/environment/holdpondff.pdf. accessed April 25, 2007.

Fields, W.J. 1971. Hydrologic and water quality characteristics of beef feedlot runoff. Unpublished M.S. Thesis, Kansas State University, Manhattan, Kansas. cited in Larson et al., 1976.

Filip, D.S., E.J. Middlebrooks and D.B. Porcella. 1975. Chemical and biostimulatory properties of cattle feedlot runoff. Water Res. 9: 573-579.

Gilbertson, C.B. and J.A. Nienaber. 1973. Beef cattle feedlot runoff-physical properties, TASAE, 16: 997-1001.

Gilbertson, C.B., J.A. Nienaber, J.L. Gartung, J.R. Ellis,and W.E. Splinter. 1979. Runoff control comparisons for commercial beef cattle feedlots. TASAE 22:842-849.

Gilbertson, C.B., J.A. Nienaber, T.M. McCalla, J.R. Ellis, and W.R. Woods. 1972. Beef cattle feedlot runoff, solids transport and settling characteristics. TASAE 15:1132-1134.

Gilbertson, C.B., J.R. Ellis, J.A. Nienaber, T.M. McCalla and T.J. Klopfenstein. 1975. Physical and Chemical properties of outdoor beef cattle feedlot runoff. Nebraska Agric. Exp. Stn. Res. Bull. 271:1-16. (Chap 1 Olson thesis)

Gilbertson, C.B., R.N. Clark, J.C. Nye and N.P. Swanson. 1980. Runoff control for livestock feedlots: state of the art. Trans. ASAE 23: 1207-1212 (Chapt 2 Olson thesis).

Gilbertson, C.B., T.M. McCalla, J.R. Ellis, and W.R. Woods. 1971. Characteristics of Manure Accumulations removed fom outdoor, unpaved, beef cattle feedlots. Pages 56-59 in International symposium on livestock wastes. Columbus, Ohio, US. April 19-22, 1971.

Gilbertson, C.B., T.M. McCalla, J.R. Ellis, O.E. Cross, and W.R. Woods. 1970. The effect of animal density and surface slope on characteristics of runoff, solid wastes and nitrate movement on unpaved beef feedlots. Univ. of Nebraska, Lincoln, The Agri Experimental Sattion. SB508.

Gilbertson, C.B., T.M. McCalla, J.R. Ellis, O.E. Cross, and W.R. Woods. 1971. Runoff, solid wastes, and nitrate movement on beef feedlots. Journal Water Pollution Control Federation. 43(3)483-493.

Gilbertson, C.B., T.M. McCalla, J.R. Ellis, O.E. Cross, W.R. Woods. 1971. Characteristics of runoff, solids, wastes, and nitrate movement on unpaved beef feedlots as affected by animal density and feedlot slope. Jour. Water Pollution Control Fed. 43:483-493.

Gillund, G.G., B. Kennedy, R. Coleman, N. MacAlpine, B. Kotelko, and P. Penney. 1996. Environmental sustainability of intensive livestock operations. Paper No 96-202. CSAE Annual Meeting, July 7-10, 1996, Letbridge, Alberta.

Gray, D. M., Landine, P. G., and Granger, R. J. 1985. Simulating infiltration into frozen prairie soils in stream flow models. Can. J. Earth Sci., 22, 464-474.

Grub, W., R.C. Albin, D.M. Wells and R.Z. Wheaton. 1969. Engineering analyses of cattle feedlots to reduce water pollution. Trans. ASAE 12: 490-492, 495.

Hargreaves, G.H., and Z.A. Samani. 1985. Referenc e crop evapotranspiration from temperature. Appl. Eng. Agr., 1(2):96-99.

Harner, J.P. and J.P. Murphy. 1998. Planning Cattle Feedlots. Dept of Biological and Agricultural Engineering, Kansas State University Agricultural Experimental Station and Cooperative Extension Service. (Harner n Murphy 1998.pdf)

Hauser, V.L. 1975. Design runoff volumes from feedlots in southwestern Great Plains. In Managing Livestock wastes (Proceedings, International Symposium). ASAE Proc-75 pp. 426-428.

Heatwole, C.D., P.L. Diebel, J.M. Halstead, S.S. Batie, R.A. Kramer, and D.B. Taylor. 1989. management and policy effects on potential groundwater contamination from dairy waste. Paper No. 89-4090. ASAE/CSAE Summer meeting, Quebec, PQ, June 25-28, 1989.

Hyder, D.N., Bement, R.E., and Norris, J.J. 1968. Sampling requirements of the water-intake method of estimating forage intake by grazing cattle. J. Range Manage. 21: 392-397.

Jury, W., W.R. Gardner, and W.H. Gardner. 1991. *Soil Physics*. John Wiley and Sons, Inc., New York, USA.,

Kang, S.F., L.T. Fan, E.S. Lee and L.E. Erikson. 1970. Modeling feedlot runoff pollution I. Analog simulation. Trans. ASAE 12: 859-863.

Kennedy, B., G. Gillund, B. Kotelko. 1995. Infiltration studis under operating pens in a commercial feedlot. Paper PNW95-101. 50th Annual Regional Converence Pacificic Northwest Section ASAE, Harrison Hot Springs, Oct 1-3, 1995.

Kennedy, B., G.G. Gillund, N. MacAlpine, R.N. Coleman, B. Kotelko, M. Kotelko, N. MacAlpine and P. Penny. 1997. Feedlot run-off impact on the environment. ASAE Paper No. 97-2156. Minneapolis, Minnesota. US. Aug 10-14, 1997, 9 pp. (Olson thesis Chap 1).

Kennedy, B., R. N. Coleman, G. M. Gillund, B. Kotelko, M. Kotelko, N. MacAlpine, and P. Penney. 1999. Feedlot Runoff: Volume 1: Quantity and quality of rainfall and snowmelt runoff from pens. CAESA Research Project RES-109-94. Alberta Agriculture, Food and Rural Development.

Kennedy, Brian , Grant Gillund, Page Penney-Stuart, 2000. Practical Manure Spreading. Farming for the Future On-Farm Demonstration Project #98NE14.

Kennedy, Brian, Richard N. Coleman, Grant M. Gillund, Bernard Kotelko, Mike Kotelko, Neil MacAlpine, Page Penney, 1999. Feedlot Runoff, Volume 1: Quantity and quality of rainfall and snowmelt runoff from pens. CAESA Research Project RES 109-94.

Kizil, U. 2003. Development of a software program for feedlot hydrology/nutrient management and GIS database for North Dakota. Ph.D. Dissertation North Dakota State University, Department of Agricultural and Biosystems Engineering, Fargo, North Dakota.

Kizil, U. and J. Lindley. 2002. Determination of Runoff Curve Number for a Bison Feedlot. 2002 ASAE/CSAE North-Central Intersectional Meeting, Saskatoon, SK, Sept 27-28, 2002. Paper No. MBSK 02-302, 12 pp.

Kizil, U. and J.A. Lindley. Spatial Evaluation of feedlot runoff and FeHyd computer program. ASAE/CSAE intersectional conference (2002 or 2003).

Komor, S.C. and D.S. Hansen. 2003. Attenuation of Runoff and Chemical Loads in Grass Filter Strips at Two Cattle Feedlots, Minnesota, 1995-98. Water-Resources Investigations Report 03-4036, U.S. Geological Survey.

Kreis, R.D., M.R. Scalf, and J.F. McNabb. 1972.Characteristics of rainfall runoff from a beef cattle feedlot.EPA-R2-72-061. U.S. Environmental Protection Agency, Corvallis, OR, 43 pp

Laguë, C., H. Landry, and M. Roberge. 2005. Engineering of land application systems for livestock manure: A review. Canadian Biosystems Engineering 47:6.17-6.28.

Larons, C.L., L.G. James, P.R. Goodrich, and J. Bosch. 1976. Performance of Feedlot Runoff Control Systems in Northern Climates. Transactions of ASAE: 1175-1180.

Lehman, R., and R. Clark. 1975. Effect of feedyard runoff on soil infiltration rates. Journal of Environmental Quality. 4(4): 437-439. (have electronic summary 'Lehman and Clark 1975.doc')

Linderman, C.L. and J.R. Ellis. 1978. Quality variation of stored feedlot runoff. Trans. ASAE. 21: 337-348.

Lorimor, J., S. Shouse, and W. Miller. 2002. Designing Settling Basins for Open Feedlots. Iowa State University, University Extension.

Lorimor, J., S. Shouse, and W. Miller. 2002. Vegetative filter strips for open feedlot runoff treatment. Iowa State University, University Extension.

Lorimor, J.C., L.N. Mielke, L.F. Elliott, and J.R. Ellis. 1972. Nitrate concentrations in groundwater beneath a beef cattle feedlot. Water Res. Bull. 8(5):999-1005.

Lott, S.C., M.E. McKay, and W. Horwood. 1990. Kinematic modeling of feedlot runoff. In The Institution of Engineers Australia Conference on Agricultural Engineering: 428-431. Nov 11-14, 1990. Toowoomba Queensland. Lott et al, 1990.

Lott, S. C., Peter J. Watts, John R. Burton, 1994. Runoff from Australian Cattle Feedlots. Proceedings of the Great Plains Animal Waste Conference on Confined Animal Production and Water Quality, October 19-21 Denver, Colorado. GPAC Publication Number 152. Pgs 44-53.

MacAlpine, N.G. Gillund, B. Kennedy, R. Coleman, W. Sawchuck, B. Kotelko, S. Ahmed and L.P. Penny. 1996. Hydrology of a feedlot. CSAE, AIC annual conf, Paper No. 96-203. Lethbridge, Alta, Canada. July 7-10, 1996.

Madden, J.M. and J.N. Dornbush. 1971. Measurement of runoff and runoff carried waste from commercial feedlots. Pages 44-47 in International symposium on livestock wastes. Columbus, Ohio, US. April 19-22, 1971.

Madden, M. and J. N. Dornbush, 1974. Livestock Waste Management, ASAE, pgs. 44-47.

Manges, H.L., L.A. Schmid, and L.S. Murphy. 1971. Land disposal of cattle feedlot wastes. Pages 62-65 in International symposium on livestock wastes. Columbus, Ohio, US. April 19-22, 1971.

Maule, C, W. Helgason, S. McGinn, and H. Cutworth. 2006. Estimation of standardized reference evapotranspiration on the Canadian Prairies using simple models with limited weather data. Canadian Biosystems Engineering 48:1.1-1.11 http://www.engr.usask.ca/societies/csae/journal.html

Maule, C.P. and T.A. Fonstad. 2002. Solute and moisture flux beneath cattle feedlot pens. Transactions of the ASAE, 45(1):73-81.

McAllister, T., F. Larney, J. Miller, J. Yanke and I. Walker. 1998. Wood chip vs. straw bedding. The Canadian Cattleman Magazine 61:26-30.

McAllister, Tim, Frank Larney, Jim Miller, Jay Yanke and Ian Walker, 1999. Comparing Wood Chips vs. Straw for Bedding in the Feedlot. Southern Alberta Feedlot Review, January 1999, Volume 1, Issue 1.

McCullough, M.C., D.B. Parker, C.A. Robinson, and B.W. Auvermann. 2001. Hydraulic conductivity, bulk density, moisture content, and electrical conductivity of a new sandy loam feedlot surface. Applied Engineering in Agriculture 17(4): 539-544.

Meat and Livestock Australia. 2002. Summer feeding of feedlot cattle. On Farm Tips and Tools. Feedlot: F11. (electronic pdf file 'summerfeed..pdf')

Meilke, L.N. and A.P. Mazurak. 1976. Infiltration of water on a cattle feedlot. Transactions ASAE 19:341-344.

Mielke, L.N., N.P. Swanson and T.M. McCalla. 1974. Soil profile conditions of cattle feedlots. J. Environ. Qual. 3:14-17.

Miller, J, T. Curtis, B. Beasley, T. Ormann, F. Larney, T. McAllister,and B. Olsond. 2004. Influence of soil texture on potential leaching from feedlots. Final Report to Alberta Beef Producers: Project No. 2001ACC003.

Miller, J.J, B.P. Handerek, B.W. Beasley, E.C.S. Olson, L. J. Yanke, F.J. Larney, T.A. McAllister, B.M. Olson, L. B. Selinger, D. S. Chanasyk, and P. Hasselback. 2004. Quantity and quality of runoff from a beef cattle feedlot in southern Alberta. Journal Environmental Quality 33:1088-1097.

Miller, J.J., B. Handerek, E.C.S. Olsen, F.J. Larney, T.A. McAllister, L.J. Yanke, D.S. Chanasyk, B.M. Olson, L.B. Selinger, and P. Hasselback. 2003. Chapter 4. Quantity and quality of runoff from a beef feedlot in southern ALberta. In Managing feedlot manure to protect water quality and human health. Final Report. CABIDF, Project #97AB061. J.J. Miller (ed.).

Miller, J.J., B. Handerek, E.C.S. Olson, F.J. Larney, T.A. McAllister, L.J. Yanke, D.S. Chanasyk, B.M. Olson, L.B. Selinger, and P. Hasselback. 2003. Managing Feedlot Manure to Protect Water Quality and Human Health, Chapters 2, 4, 5 and 6. From Canada-Alberta Beef Industry Development Fund Project No. 97AB061 Final Report, Alberta Agricultural Research Institute, Alberta Agriculture, Food and Rural Development, Edmonton, AB., pp. 1-498.

Miller, W.D. 1971. Subsurface distribuitonof nitrates below commercial cattle feedlots, Texas High Plains. Water Res. Bull. 7(5):941-950.

Miner, J.R. 1967. Water pollution potential of cattle feedlot runoff. PhD. Dissertation, Kansas State University.

Miner, J.R., L.R. Fina, J.W. Funk, R.I. Lipper and G.R. Larson. 1966. Stormwater runoff from cattle feedlots. Pages 23-27 in Management of farm animal wastes. Proceedings national symposium on animal waste management. ASAE publication No. SP-0366. Michigan State University, East Lansing, Michigan, US May 5-7, 1966. pp 23-27

Miner, J.R., R.B. Wensink, R.M. McDowell. 1979. Design and cost of feedlot runoff control facilities. EPA 600/2-79-070. Washington, D.C. (Kizal 2003)

Moore, R.J. 2007 The PDM rainfall-runoff model. Hydrol. Earth Syst. Sci. 11(1): 483-499.

Morrison, S.R., G.P. Lofgreen, and T.E. Bond. 1971. Feedlot manure management in a desert climate. Pages 60-61,65 in International symposium on livestock wastes. Columbus, Ohio, US. April 19-22, 1971.

Mosier, A.R., K. Haider, and F.E. Clark. 1972. Water soluble organic substances leachable from feedlot manure. JEQ 1:320-323.

Nicholaichuk, W. 1967. Comparative watershed studies in southern Saskatchewan. Trans. ASAE 10(4): 502–504.

Nienaber, J. A., C. B. Gilbertson, T. J. Klopfenstein, S. D. Farlin and T. M. McCalla. 1974. Animal Performance and Lot Surface Conditions as Affected by Feedlot Slope and Animal Densities. Proceedings from International Livestock Environment Sym posium, Lincoln, Nebraska. pp. 130-I37.

Nolan, S.C., L.J.P. van Vliet, T.W. Goddard, and T.K. Flesch. 1997. Estimating soil loss from rainstorms. Canadian Journal of Soil Science 77(4):669-676.

NRCS (Natural Resources Conservation Service. 2001. Part 630 Hydrology. http://www.wcc.nrcs.usda.gov/hydro/hydro-techref-neh-630.html. Accessed 2006-07.

Olson, E.C.S., J.J. Miller, D.S. Chanasyk, B.M. Olson, F.J Larney, T.A. McAllister, L.J. Yanke, L.B. Selinger, and P. Hasselback. 2003. Chapter 2. Effects of Bedding Type and Within-Pen Location on Feedlot Runoff and Infiltration. In Managing feedlot manure to protect water quality and human health. Final Report. CABIDF, Project #97AB061. J.J. Miller (ed.).

Overcash, M.R. and R.L. Phillips. 1978. Dairy Feedlot Hydrology. Transactions of the ASAE:1193-1198, 1208.

Parker, D.B., D.E. Eisenhauer, D.D. Schulte, and D.L. Martin. 1999. Modeling seepage from an unlined beef cattle feedlot runoff storage pond. Trans. ASAE 42, 1437-1445.

Phillips, R.L. 1981. Maps of Runoff Volumes from Feedlots in the United States. 4th International Proceedings ASAE. pp 274-277.

Powers, W., K. Bormann, and W. Miller. 2003. Developing whole farm nutrient plans for feedlots. Iowa State University, University Extension. (Powers ea 2003.pdf)

Powers, W.J. and H.H. Van Horne. 2001. Nutritional implications for manure nutrient management planning. Applied Engineering in Agriculture. 17(1):27-39

Queensland Government. 2003. Feedlot waste management manure production data. Dept of Primary Industry and Fisheries. File IL0043

Robbins, J.W.D. 1979. Impact of unconfined livestock activities on water quality. Transactions ASAE: 1317-1323.

SAF (Saskatchewan Agriculture and Food). 1999. Farmfacts: Holding Pond Site Selection and Design. 3M ISSN 0840-9447 LOHP0199. http://www.agr.gov.sk.ca/docs/production/holdpondff.pdf

SAF (Saskatchewan Agriculture and Food). 2004. Beef Cattle Housing and Feedlot Facilities. Government of Saskatchewan. http://www.agr.gov.sk.ca/docs/production/housing_feedlot_facilities.asp. Accessed Jan 2007.

Safley, L.M., C. Dupoldt, F. Geter, D. Stettler, and T. Murphy. 1996. Chapter 10. Agricultural Waste Management System Component Design. In J. Krider (ed.) Agricultural Waste Management Field Handbook. National Engineering Handbook Part 651. Natural Resoruces Conservation Service. http://www.wcc.nrcs.usda.gov/awm/awmfh.html

SAFRR (Saskatchewan Agriculture, Food and Rural Revitalization). 2003. Environmental Review: Guidelines for Intensive Livestock Operations. 1M ISBN 0-88656-702-5. http://www.agr.gov.sk.ca/docs/programs_services/ILOreview2002.pdf. Accessed Jan 2007.

Schofield, C.P. 1988. Water absorption by spring-barley bedding straw. Biol Wastes 26:133-144.

Schuman, G.E. and T.M. McCalla. 1975. Chemical characteristics of a feedlot soil profile. SS 119(2):113-118.

SCS (Soil Conservation Service). 1972. Section 4: Hydrology In National Engineering Handbook. SCS, referred to in SWAT 2005.

SEACOR. 1995. Test Drilling Program, Proposed River Ridge Cattle Corp. Feedlot, South of Eston, Sasktachewan. May 11, SEACOR, Environmental Engineering, Inc.

Sommerfeldt, T.G., U.J. Pittman and R.A. Milne. 1973. Effect of feedlot manure on soil and water quality J. Environ. Qual 2:423-427.

Southcott, P.H. and S.C. Lott. 1997. Preliminary results on soil permeability and physical characteristics of feedlot pens. Preliminary results on soil permeability and physical characteristics of feedlot pens. Proc. Of the 7th Aust. And NZ Conf. on Geomechanics, Adelaide. 6 pp.

Swanson, N.P. 1972. Hydrology and characteristics of feedlot runoff. P. 71-80. In Proc. Of Seminar on control of agricultural-related pollution, Lincoln, NE 24-25 July 1972. Great Plains Agric. Council, Lincoln, NE

Swanson, N.P., L.N. Mielke, J.C. Lorimner, T.M. McCalla and J.R. Ellis. 1971. Transport of pollutants from sloping cattle feedlots as affected by rainfall intensity, duration and recurrence. Pages 51-55 in International symposium on livestock wastes. Columbus, Ohio, US. April 19-22, 1971.

SWAT (Soil and Water Assessment Tool). 2005. Equations: Surface Runoff, Section 2 Chapter 1. SWAT Theoretical Documentation, Version 2005. http://www.brc.tamus.edu/swat/doc.html

Sweeten, J.M., T.H. Marek, and D. McReynolds. 1995. Groudnwater quality near two cattle feedlots in Texas High Plains: A case study. ASAE 11(6): 845-850.

Swenson, D.A. 1975. Feedlot runoff control systems. M.Sc. Thesis. Fargo, North Dakota State University, Ag. Eng Dept.

Tossell, R.W., G.J. Wall, R.P. Rudra, W.T. Dickinson, and P.H. Groenevelt. 1990. The Guelph rainfall simulator II: part 2 – a comparison of natural and simulated rainfall characteristics. *Canadian Agricultural Engineering*. 32: 215-223.

Tossell, R.W., W.T. Dickinson, R.P. Rudra, and G.J. Wall. 1987. A portable rainfall simulator. Can. Agric. Eng. 29, 155-162.

USDA. (U.S. Dept. of Agriculture), Soil Conservation Service. 1973. USDA runoff estimation method. Publication SCS-TP-149. April, 1973.

USDA. 1996. Appendix 10C – Runoff from feedlots and evaporation. 651.1070. In Agricultural Waste Management System Component Design. Part 651. Agricultural Waste Management Field Handbook. http://www.wcc.nrcs.usda.gov/awm/awmfh.html

Utley, P.R., N.W. Bradley and J.A. Boling. 1969. Effect of restricted water intake on feed intake, nutrient digestibility and nitrogen metabolism in steers. J. Anim. Sci. 31:130-135.

Vanderholm, D.H. 1975. Nutrient losses from livestock waste during storage, treatment, and handling. In F.R. Hore et al., eds., Managing Livestock Wastes, Proceedings of the 3rd International Symposium on Livestock Wastes, pp. 282–284. American Society of Agricultural Engineers, St. Joseph, MI.

Watts, P.J. and M.E. McKay. 1986. Simulation Modeling of Cattle Feedlot Hydrology. Conference on Agricultural Engineering, Adelaide, Australia. Institution of Engineering, Barton, ACT, Australia, pp 393-398.

Wensink, R.B. and J.R. Miner. 1975. A Model to Predict the Performance of Feedlot Runoff Control Facilities at Specific Oregon Locations. Transactions of the ASAE: 1141-1145, 1150.

White, Lisa. Feedlot Hydrology. M.Sc. Thesis, University of Saskatchewan, Dept of Agricultural and Bioresources Engineering. Feb. 2006. Electronic version available at http://library2.usask.ca/etd/ETD-search/search

White,L. no date. Literature Search and Review for Nutrient Movement from Manure Spreading Areas In Floodplains. (electronic file 'White 200X.doc').

Wise, G. nd D.L. Reddell. 1973. Water quality of storm runoff from a Texas beef feedlot. ASAE Paper No. 73-441. ASAE, St. Joseph, Mich. 49085

Woerner, B. and J. Lorimer. Alternative treatments to minimize water pollution from open feedlots. Dept of Agricultural and Biosystems Engineering, Iowa State University.

Zovne, J.J., T.A. Bean, J.K. Koelliker, and J.A. Anschutz. 1977. Model to evaluate feedlot runoff control systems. Proceedings ASCE 103 (No. IR1):79-92.

Water Balance of a Prairie Cattle Feedlot Pen

Lisa White[1], Charles Maulé[2] and Terry Fonstad[2]

[1]Graduate student. [2]Professors. Agricultural and Bioresource Engineering, 57 Campus Drive, University of Saskatchewan, Saskatoon, SK, S7N 5A9

Proceedings From Soils and Crops Workshop, University of Saskatchewan, Feb 17-18, 2005

Key Words: Soil water balance, infiltration, runoff, cattle, feedlot

Abstract

The overall purpose of this study is to define the water balance of feedlot pens in a Saskatchewan cattle feeding operation. Although the initial intention of the study was focused upon an active feedlot circumstances resulted in our year of analysis being on an recently abandoned feedlot. During the study year (Sept 2003 to Aug 2004) there was very little precipitation until May 2004. Weirs in operation for only part of the summer recorded no runoff. Winter precipitation was very low (34 mm) and there was no observed runoff from it. Runoff models, using lab and field parameters found that at the most there might have been runoff from only one event, that of 26 mm 24 hr rainfall, and this would have only occurred on a pen scraped of manure. Drainage beneath 60 cm soil depth was zero mm. Of the 339 mm of precipitation that fell during the study year, some of it was stored within the manure pack and the rest lost as evaporation.

Introduction

Current provincial siting regulations require design of holding ponds for at least 7.5 cm (3 inches) of runoff from the contributing area. Many jurisdictions use the volume of a 1 in 25 year-24 hour rainfall event to determine the holding pond volume. For Saskatchewan this corresponds closely to 7.5 cm. As it stands now, it is unknown if this regulation is sufficient or overcompensates for the actual runoff from feedlot penning areas. ***The objective of this study is to quantify the water balance of a field lot pen.*** Evaluation of a water balance involves determination and measurement of processes that add water (input) or remove water (output) from the system along with changes in water storage of components within the system. Although it was originally the intention of quantifying the water balance of an active feedlot circumstances resulted in the study year being for an inactive feedlot. The following water balance components and processes were determined or measured for a one year period: precipitation, evaporation, runoff, infiltration soil, change in soil moisture to a depth of 0.60 m, and water draining below a depth of 0.6 m. The findings from this study will be later used to develop a daily soil water balance model for cattle feedlot pens that incorporates climatic, texture, and water input conditions so as to determine the occurrence and amount of runoff.

Materials and Methods

The study site was the River Ridge feedlot, which is located approximately 20 km south of Eston and about 50 km SE of Kindersley on the north side of the South Saskatchewan River. The feedlot was first established in 1996 as a community co-op venture consisting of 8 pens, each 75 by 75 m in area. During 2002 another 8 pens were established immediately to the north of the

previous pens. Construction consisted of removal of the top soil and grading the pens such that runoff collected in holding ponds on the perimeter of the feedlot area. .

Our study took place in two pens, one that was first stocked in 1996 and another first stocked in 2002. Stocking density of each the two study pens had been approximately 100 backgrounding cattle weighing about 360 kg each. The pens were 75 m by 75 m in area, thus the stocking density was approximately 56 m^2 per head. The stocking density used at the feedlot was less than that of other North American feedlots, which is generally between 7 and 16 m^2 per head (Davis, 2002). Bedding consisted of straw. The pens were cleaned in the fall of each year. There were cattle present in pen 4 until August 2003 and July of 2003 in pen 6. Our study year was from Sept 1, 2003 until Aug 31, 2004.

Table 1. Parameters Measured and Methods Used for Study

Parameter	Instrumentation or Method	Reference
Rain intensity and amount	Texas tipping bucket	
Daily snowfall	Kindersley	Environment Canada
Potential evapotranspiration	Standardized ET	ASCE 2002
Potential evapotranspiration	Hargreaves	ASCE 2002
Infiltration, Ksat	Double ring infiltrometer	
Infiltration, Ksat & runoff, measured	Guelph Rainfall simulator	Tossell 1987
Infiltration & Runoff, calculated	Green-Ampt	Chu 1997
Runoff actual, measured	V-notch weir	
Runoff, calculated	USDA SCS	Schwab et al., 1996
Snowmelt runoff	Observation and calculated	Gray et al., 1985
Ksat	undisturbed cores	falling head
Drainage	chloride tracer	Maule and Fonstad (2002)
Bulk density (soil, manure)	undisturbed cores, clod, settling	
Moisture content	undisturbed & disturbed cores, TDR	

Results

Soil Properties: The texture of the top 60 cm of the feedlot pens was a loam (18% clay and 51% sand). The top 5 cm of soil had an organic carbon content of 0.68%. The bulk density of the soil was highest in the upper 10 cm (1.67 g/cm^3) and was 1.35 g/cm^3 at 20 to 25 cm depth.

Manure Properties: During the study period there were no cattle in the pens, however the manure pack had been left at our request. The manure pack at the start of the study and in May 2004 was generally in a dry state. Its average thickness was 11 cm consisting of about 6 cm of dry loose granular (several mm to 10 cm 'pieces') material overlying about 5 cm of hard compacted manure. The granular layer, upon sampling, was very dry and had a dry bulk density of 0.44 g/cm^3. Upon saturation (in the lab) the volumetric moisture content increased to 0.82 m^3/m^3 and the bulk density decreased to 0.36 g/cm^3 due to expansion.

Climate: During the study period (Sept 1, 2003 to Aug 31, 2004) the feedlot climate station was operational only 45% of the time. Equipment failures combined with distance resulted in an incomplete data set. To supplement the missing data, daily temperature and precipitation was used from Kindersley (Environment Canada), after correction. During the one year study period the average temperature was 3.0°C and the total precipitation was 339 mm. This was comparable

to the long term average (1971-2000) of 2.9 °C and total precipitation of 326 mm. The warm season (April thru October) for the study period was slightly cooler and wetter than normal (11.2°C as compared to 11.8°C and 305 mm as compared to 254 mm. Snowfall (as measured at Kindersley) was only 34 mm of water, lower than long term normal of 59 mm.

Wetting and Drying events: During the operational time of the feedlot met station the greatest intensity recorded on the tipping bucket was 4.5 mm in 30 minutes on June 11, 2004. There were 46 days with rainfall greater than 1.0 mm (including data supplemented from Kindersley) of which there were 11 events larger than 10 mm/day of which the largest 4 events were 26, 19, 19, and 16 mm on June 3, June 11, Aug 4, and Aug 7 respectively. Two wet periods occur during the study period (Fig 1); June 2-12 (96 mm) and July 27 to Aug 7 (71 mm) (Fig. 1). The study year started off very dry (Aug 2003 had only 17 mm) and continued so until May 2004 by which only 59 mm had occurred with 34 mm of it during winter. Potential evapotranspiration (PET) for the study year was 733 mm (Fig. 1). From analysis of longterm Kindersley rainfall data (1911 to 2004) it can be expected that a maximum 24 hour rainfall of 85 mm will occur once in 30 years and a rainfall of 35 mm can be expected once a year.

Recorded and observed runoff events: The weir was in operation for only a short time (July 1 2004 to Aug 31, 2004), during which there were no runoff events recorded. During this period there were 5 rainfall events greater than 10 mm/d of which the largest was 19 mm on Aug 4. During the study year there were no observed runoff events, during site visits, nor any evidence of (from ponded water in the storage pond or that of fresh erosion rills in the sides of the storage pond). The snowpack was very thin and a site visit during spring melt revealed no runoff from the pens into the storage ponds.

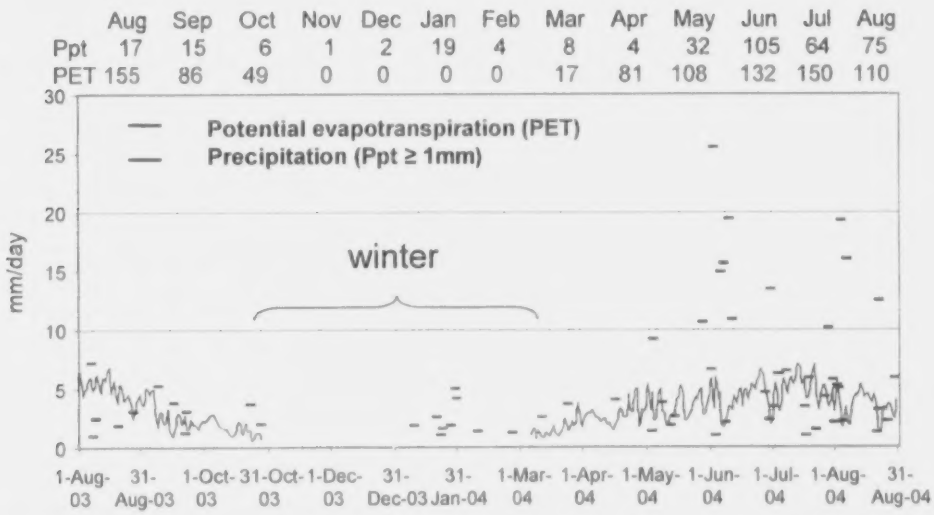


Figure 1. Daily potential evapotranspiration and precipitation, Aug 1 2003 to Aug 31 2004. Values in top are in mm/month.

Drainage: Chloride concentrations in the upper 10 cm of soil underlying the manure pack was between 337 and 481 mg/L (2:1 extract) and reduced to 4 and 51 mg/L by 40 to 50 cm depth. There was some variation with depth, thus it is difficult to interpret what was background Cl. Within the nearby agricultural field Cl concentrations were between 4 and 7 mg/L to a 2 m depth. Based upon previous work (Maule and Fonstad 2002) seepage rates are very low (2 to 8 mm/yr) and the higher chloride concentrations at depth (eg., 150 mg/L) may not likely to be due to manure; it could be due to parent material, construction, or old farmstead buildings. Given the dry year experienced it is unlikely that there was any drainage within the study year.

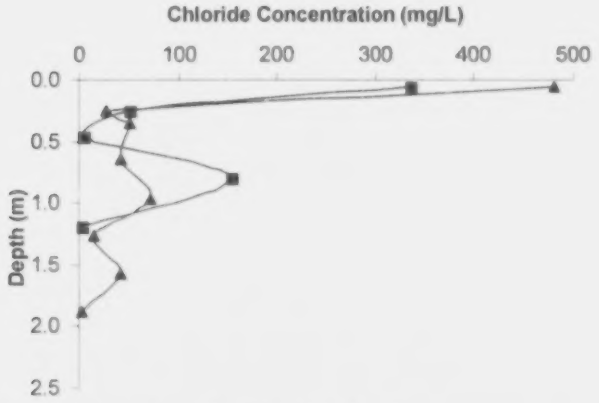


Figure 2. Chloride concentration of pen 4 with depth.

Changes in soil moisture storage: Soil samples taken in September 2003 showed bare soil and soils with a manure pack on top having 113 mm and 124 mm of moisture in the upper 60 cm respectively. By Aug 24, 2004 the upper 60 cm of bare soil had 137 mm of moisture, while that of the upper 60 cm of soil with an overlying manure pack had 116 mm. Although there was definitely a drying trend from Sept 2003 until June 2004, the manure pack and bare soil gained moisture from the July and August rains (Fig. 3). Manure pack and soil samples taken for moisture content from July 6 to Oct 6, 2004 showed the manure pack increasing in moisture content from July 19 to Aug 24 by 50 mm, while the soil beneath the manure pack increased by 4 mm, and soil with no manure pack, by 17 mm (Fig. 3). For soil at the depth interval 40-60 cm change during the same period was 0 mm. During this period, rainfall was 89 mm with most of it occurring from July 19 to Aug 10. Potential evapotranspiration was 144 mm.

Instrumental infiltration and saturated hydraulic conductivity; Steady-state infiltration on the feedlot manure pack, as measured with the double ring infiltrometer and the rain fall simulator was 5.5×10^{-3} cm/s and 8.9×10^{-4} cm/s respectively. Laboratory cores provided saturated manure hydraulic conductivity values of 3.5×10^{-4} cm/s. The rainfall simulator measured steady-state infiltration into the scraped soil surface of 8.1×10^{-3} cm/s whereas the lab Ksat values were 3 orders of magnitude lower, at 5.1×10^{-6} cm/s. It was difficult to install the metal sides of the rainfall simulator and lateral flow could have accounted for the higher rates. The lab measurements were on undisturbed clods and the lack of naturally occurring cracks could have also resulted in lower rates than would have occurred in the field.

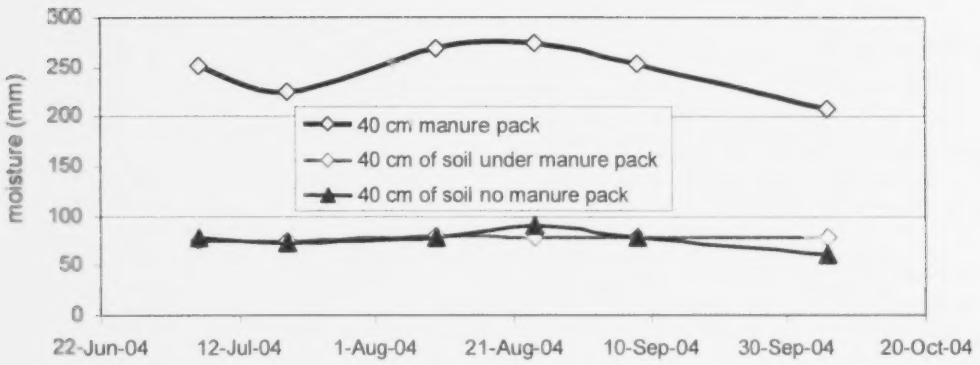


Figure 3. Moisture content of manure, soil underlying manure and bare soil of feedlot pens.

Instrumental rain and runoff; Where the rainfall simulator tests (at rain rates between 34 and 55 mm/hr) were done on the manure pack it generally took at least 2 hrs (and in once case 8 hrs) to achieve runoff. This was due to the dry state of the manure pack, which absorbed much of the rainfall. Rainfall simulator tests on the bare pen soil (manure was scraped away) resulted in runoff occurring within 1 to 6 minutes.

Modeled infiltration and runoff; Given the incomplete data set by the weir, two models (Green-Ampt infiltration and SCS runoff) were used to determine whether or not runoff might have occurred from the four heaviest rains (16, 19, 19, and 26 mm). Using the Green-Ampt equation obtained reasonable fit (time to occurrence of runoff and runoff rate) rainfall simulation runoff for soil with a Ksat of 5.1×10^{-5} cm/s and for a manure Ksat of 3.5×10^{-4} cm/s. Analysis of Kindersley and Saskatoon rainfall intensity-duration data (Environment Canada) indicates that for 24 hr rain amounts of 19 to 25 mm, that the median 5 minute intensity rainfall intensity will be of about 20 mm/hr, with 80% of the total rain amount falling within 6 hrs. The Green-Ampt method indicates that for these four storms there would be no runoff for the manure pack, wet or dry and for a bare packed soil surface there would only be at the most 5 mm runoff if the antecedent soil moisture was close to saturation.

The USDA Soil Conservation Service (SCS) runoff method have been used by others to model feedlot runoff (Kennedy, 1999; Miller et al., 2003) and found that curve numbers varied between 52 and 97 depending on antecedent moisture, stocking density, and storage values of the manure pack. As no runoff was recorded during our study period we looked at the effects of using a SCS curve number of 60, to represent dry manure and that of 90 for a scraped pen. The 24 rainfall required to produce 5 mm of runoff for a SCS curve number of 60 was 50 mm and for a SCS curve number of 90 was 20 mm. A one in 30 year rainfall of 85 mm will produce about 20 mm of runoff from a dry manure pack (SCS of 60) and 80 mm from a pen soil surface (SCS of 90).

Findings

We considered the soil and manure water balance of an inactive feedlot during the period of Sept 1, 2003 to Aug 31, 2004. The cattle were taken from the pens in July 2003. Analyses are not completed for the manure pack moisture contents, but the following water balance components were determined for the one year period:

Total precipitation: 339 mm (of which 34 mm was snow)
Bare soil surfaces in feedlot pens

- change in soil moisture to 60 cm: 23 mm gain
- probable runoff: 5 mm
- probable drainage: 0 mm from rains
- evaporation: 311 mm (=339 – 23 – 5)

Manure pack in feedlot pens

- change in underlying soil moisture to 60 cm depth: -8 mm
- change in manure pack moisture content: unknown
- probable runoff: 0 mm
- probable drainage: 0 mm
- evaporation: 339 mm

Acknowledgments

Funding for this project is provided by Saskatchewan Agriculture Development Fund. The Prairie Farm Rehabilitation Administration is acknowledged for drilling and installation of piezometers, drill log interpretation and geotechnical laboratory analysis of core samples. Personnel at the River Ridge Feedlot are thanked for access permission and project support. Daryl Rinas, Crystal Halliday, and Marc White are acknowledged for their field help.

References

ASCE 2002. The ASCE Standardized Reference Evapotranspiration Equation. Environmental Water Resources Institute of the American Society of Civil Engineers. Draft, revised July 9,2002.

Chu, S.T. 1997. Infiltration model for soil profiles with a water table. Trans. ASAE 40(4), 1041-1046.

Davis, J.G. , T.L. Stanton, and T. Haren (2002). Feedlot manure management no. 1.220. Published by Colorado State University Cooperative Extension. From website: http://www.ext.colostate.edu/pubs/livestk/01220.pdf

Gray, D. M., Landine, P. G., and Granger, R. J. 1985. Simulating infiltration into frozen prairie soils in stream¯flow models. Can. J. Earth Sci., 22, 464-474.

Kennedy, B. et al. 1999. Feedlot runoff: Volume 1: Quantity and quality of rainfall and snowmelt runoff from pens. CAESA Res. Project Res. 109-94. Alberta Agriculture, Food and Rural Development, Vegreville, AB.

Miller, J.J., B. Handerek, E.C.S. Olson, F.J. Larney, T.A. McAllister, L.J. Yanke, D.S. Chanasyk, B.M. Olson, L.B. Selinger, and P. Hasselback. 2003. Managing Feedlot Manure to Protect Water Quality and Human Health, Chapters 2, 4, and 6. Final Report, Alberta Agricultural Research Institute, Alberta Agriculture, Food and Rural Development, Edmonton, AB. Pp. 1-498.

Schwab, G.O., D.D. Fangmeier, and W.J. Elliot. 1996. Soil and Water Management Systems. 4th Edition. John Wiley & Sons, Inc.

Tossell, R.W., W.T. Dickinson, R.P. Rudra, and G.J. Wall. 1987. A portable rainfall simulator. Can. Agric. Eng. 29, 155-162.